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# THESIS

**A PROCESS FOR APPLYING FORECAST UNCERTAINTY IN PLANNING FOR UNDERWAY EVOLUTIONS ALONG INTENDED TRACK**

by

Shane Stoughton

September 2010

Thesis Advisor: Rebecca Stone
Second Reader: Patrick Harr

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# A PROCESS FOR APPLYING FORECAST UNCERTAINTY IN PLANNING FOR UNDERWAY EVOLUTIONS ALONG INTENDED TRACK


Shane R. Stoughton
Lieutenant Commander, United States Navy
B.S., The Pennsylvania State University, 1999


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**September 2010**

Author: Shane Stoughton

Approved by: Rebecca Stone
Thesis Advisor

Patrick Harr
Second Reader

Philip Durkee
Chairman, Department of Meteorology

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# ABSTRACT

The sensitivity of operational decision making to atmospheric forecasts is a key component of the Decision Tier, or Tier 3, of Battlespace on Demand, Naval Oceanography's operational concept. To that end, effects of different wind forecast inputs were analyzed within a modeled decision context for an aircraft carrier ammunition offload. Development of the decision context using expected distance as the utility measurement was followed by an examination of the climatology of wind events that could adversely affect an offload evolution. Two high-wind event cases from 2009 were chosen for analysis within the decision model. Ensembles from numerical weather prediction models were formed into probabilistic wind forecasts and applied to several decision scenarios. Slight changes to both the forecast inputs and the decision context itself produced different decision outcomes, which emphasized the interdependency between forecasts and optimum decisions in the modeled scenario.

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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| ACAF | Advanced Climate Analysis and Forecasting Web site |
| BOND | Battlespace on Demand |
| CSG | Carrier Strike Group |
| CVN | Nuclear Aircraft Carrier |
| DoD | Department of Defense |
| ECMWF | European Centre for Medium-Range Weather Forecasts |
| EPS | Ensemble Prediction System |
| ESRL | Earth System Research Laboratory |
| MATLAB | Matrix Laboratory |
| NetCDF | Network Common Data Form |
| NCEP | National Centers for Environmental Prediction |
| NRC | National Research Council |
| NWP | Numerical Weather Prediction |
| OZ | Offload Zone |
| PIM | Position of Intended Movement |
| SOA | Speed of Advancement |
| SSM/I | Special Sensor Microwave/Imager |

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# ACKNOWLEDGMENTS

I would like to thank my wife, Lynne, for her persistent support during this entire process. She has kept a positive outlook and created an environment in our home that was conducive to my success.

I owe gratitude to my parents as well. They have continued to support me, as they have throughout my life, by knowing just what to say at just the right time to help me focus on the present task.

While all the Meteorology and Oceanography faculty and staff at NPS have been immensely supportive, several provided specific efforts toward this thesis. My advisor, CDR Rebecca Stone, was the perfect match for my intended research efforts. Her approach to solving the problems and analyzing the decisions supported by our enterprise was something that I was very interested in exploring, and she helped me do just that. Professors Eva Regnier and Joshua Hacker taught the courses that were most influential in the development of this thesis. Bob Creasey, Professors Tom Murphree and Arlene Guest, and ENS Bill Jenkins were invaluable to me as they provided the data and the methods to analyze it. They helped me in the areas where I was weakest, and I am truly thankful for their efforts and support.

LCDR Ken Wallace is a friend and was initially a fellow student. During his subsequent tour aboard the USS Ronald Reagan (CVN 76), he was also the primary resource for helping develop the operational decision scenario upon which this thesis was based. I appreciate his efforts, especially considering that he helped me even while on sea duty.

I would like to thank the Naval Postgraduate School Foundation for helping my wife and I truly enjoy our time here. It provided countless opportunities of recreation, professional development, and camaraderie. We have been fortunate to be a part of such a special organization.

Finally, I would like to thank my classmates. They are magnificent.

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# I. INTRODUCTION

## A. MOTIVATION

Battlespace on Demand (BOND), Naval Oceanography's operational concept, is designed to generate enhanced decision-making capabilities for the warfighter (Commander Naval Meteorology and Oceanography Command (CNMOC), 2010). We sought to use a structurally simple operational decision context as an example, apply the BOND concept and currently available meteorological and statistical tools, and explore the resulting recommendations and modeled outcomes.

The decision scenario spawned from conversations with LCDR Ken Wallace, who was the OA Division Officer aboard the USS Ronald Reagan (CVN 76) during the onset of this thesis. He communicated his experiences during the time leading up to and the execution of an ammunition offload conducted during a Western Pacific deployment. Ken stressed the high level of interest decision makers had in the anticipated weather conditions beginning over a week prior to their offload. He explained that a wind speed of less than 25 knots was required to conduct the offload, and that the Carrier Strike Group (CSG) was slightly behind schedule, reducing the time available for the operation and amplifying the importance of completing it on time. There were several constraints present in the decision, including ammunition required to be offloaded prior to crossing 180° longitude, scheduled port call and Tiger Cruise personnel embarkation in Pearl Harbor, the speed and fuel consumption of other vessels in the CSG, and the wind speed threshold.

What were unclear in LCDR Wallace's case, and possibly for good reason due to the complexity and ever-changing nature of the decision context, were the alternatives available to decision makers in the event of wind forecasts in excess of 25 knots. There appeared to be some opportunity to speed up or delay, though those options were already somewhat limited due to previous delays in

transit.  There was also discussion of maneuvering around any potential high wind areas.  The opportunities available for changing speed and/or direction were reduced as time progressed.  Of course, there was the alternative of continuing as planned and dealing with any high wind conditions in real-time (K. Wallace, personal communication, 2010).

The ultimate motivations for this study were to better understand the decision context facing a CSG leading up to an underway ammunition cross-deck evolution and to explore the methods for forecasting winds in a way that positively influences that decision context.

## B. BATTLESPACE ON DEMAND

The BOND strategy is organized into four stacked layers that form a pyramid (Figure 1).  At the bottom of the pyramid is Tier 0:  Data.  The collection and assimilation of this data forms the foundation of the remaining tiers.  Next is Tier 1:  Environment.  Here, the data from Tier 0 are initialized and run through numerical models to determine the predicted environment.  Tier 2:  Performance. The predicted environment and knowledge of the operational capabilities and limitations of warfighting forces are combined into a comprehensive performance surface.  Finally, Tier 3: Decision.  Performance surfaces are applied “to specific decision-making processes to quantify risk and opportunity at strategic, operational and tactical levels (CNMOC, 2010).”

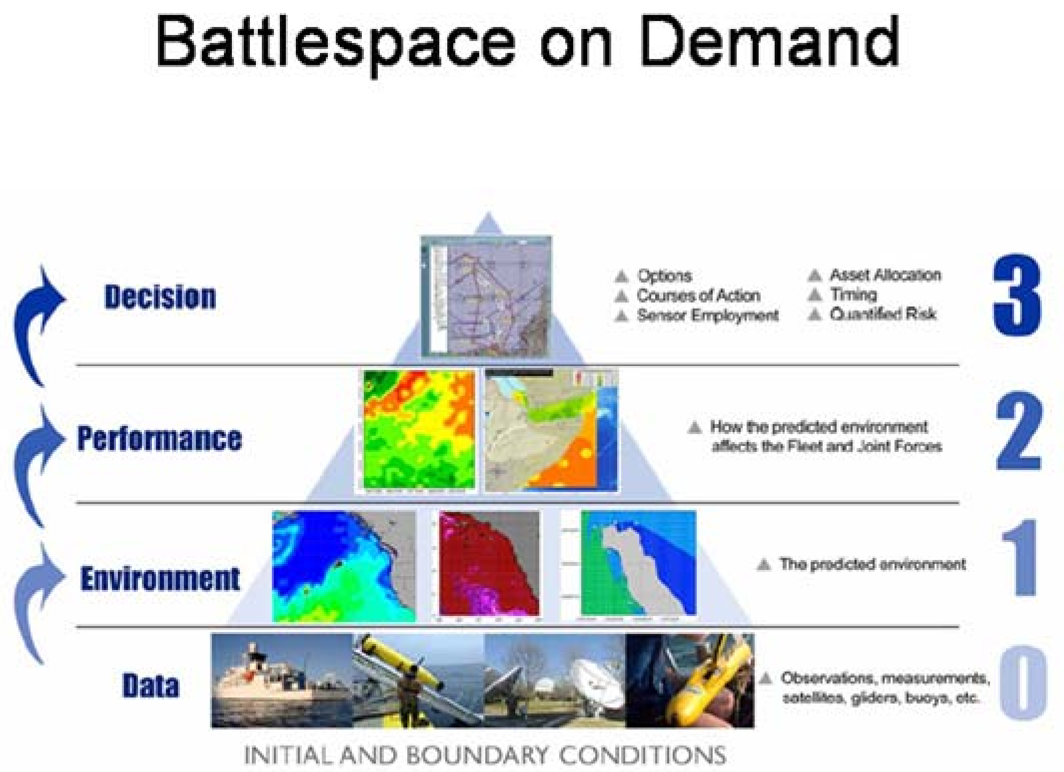


Figure 1. Battlespace on Demand (BOND 2010)

From the experiences recounted by LCDR Wallace, it seemed that, relative to the BOND pyramid, he had sufficient input from Tiers 0, 1, and 2. In addition to his ship's own observation and data collection capabilities, he had access to the Naval Oceanography Tier 0 data through the Tier 1 forecast models. He was also aware of the known effects of the predicted environment on his ship during the planned offload evolution; the wind threshold was 25 knots (K. Wallace, personal communication, 2010).

Only the connection to Tier 3 seemed to be missing, as there was no standardized method or application for quantifying the uncertainty of the future wind conditions. Moreover, the decision context surrounding what to do if high winds were forecasted was not clearly articulated. It is possible that the nature of the forecast information from the lower tiers did not allow its use in the decision

context; it is also possible that the makeup of the decision context was not precise enough to require a specific type of forecast. The usefulness of a decision context and the uncertainty information that it uses are both maximized when each are designed with the other in mind.

## C. EARLIER WORK

Research about the inclusion of uncertainty information in weather forecasts has been conducted for a long time and for a variety of applications. In 1869, Cleveland Abbe encouraged the Cincinnati Chamber of Commerce to implement "…such a system…which shall give the probable state of the weather and river for Cincinnati and vicinity one or two days in advance (National Academies Press (NAP), 2006)".

Soon after the turn of the 20th century, W. E. Cooke (1906) created a weighting scale that forecasters could apply to their own forecasts to communicate their confidence in the forecasts.

Closer to the present day, the inherent uncertainty contained in weather forecasts has been analyzed within weather-based decision contexts. The work of Allan H. Murphy (1993) focused on what makes a forecast valuable: "…it should be understood that forecasts possess no intrinsic value. They acquire value through their ability to influence the decisions made by users of the forecasts". In 2002, Zhu et al. described the usefulness of probabilistic forecasts from ensemble prediction systems (EPS) in terms of economic benefit.

# II. RESEARCH QUESTIONS AND METHODOLOGY

Springing from the objective of better understanding the operational decision and methods for meteorological forecasts to positively affect a CSG ammunition offload, we formulated research questions about both the meteorological phenomena and the decision's optimization.

First, a detailed background of the meteorological phenomena in the region of interest was necessary:

- What are the meteorological phenomena causing the operational problem?
- What are the characteristics of a high-wind event in the region in terms of size, duration, and causes?
- What is the baseline, or climatological, frequency of a high wind event?

Then, an understanding of the impacts of forecast information on the operational decision context was required:

- What statistical forecast information is essential to optimize the decision, and is it available?
- Is the forecast information certain enough to cause a decision change?
- What are the uncertainty characteristics of a forecast for a high wind event?
- Will the location of the minimum probability of high winds always be the optimum course?
- How does the uncertainty change from longer to shorter lead times?

- What effect does changing either the forecast information or the decision context have on the recommended course?

The approach to this research was to develop a decision scenario representative of an ammunition offload. The steps required include examination of the meteorological phenomena that affect that operation, evaluation of the tools available for probabilistic forecasting of the phenomena, and finally combination of all these pieces in a comprehensive decision problem under adverse weather conditions.

An example decision context was crafted, complete with objectives, constraints, alternatives, future states, and consequences. Minimization of expected distance was the method used for optimized decision recommendations.

The climatology of surface winds in the region of interest was examined. Data for the long-term mean wind speed and frequency of occurrence for specific thresholds was presented. Searches for wind events that could affect offload operations highlighted a few specific cases for further analysis.

Probability forecasts were generated from ensemble members of numerical weather prediction (NWP) model data. Application of these probability forecasts in the decision scenario allowed a comparison of probability and expected distance values for decision alternatives. The distances of course alternatives at each decision point were determined using great circle segments between the ship's current location and OZ entry, across the OZ, and OZ to Pearl Harbor, HI.

The decision scenario was implemented for two different high wind events. Adjustments to the decision scenario and forecast information suggested the sensitivity of the decision maker's choices to both the makeup of the decision context and its probabilistic forecasts.

In Chapter III, we present the decision context and our method for modeling its optimization. Chapter IV presents the information available from

climatology for long lead time planning. In Chapter V, we describe the cases we identified as high-wind events where the easterly trades exceeded 25 knots long enough to significantly impact a ship's planned evolutions along-track. In Chapter VI, we present the information available from the European Center for Medium Range Weather Forecasts and in Chapter VII demonstrate its use in this decision context. Chapter VIII considers the possible use of a single deterministic forecast in optimization, and Chapter IX presents conclusions and recommendations.

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# III. DECISION ANALYSIS

## A. BASIC THEORY AND METHOD

We modeled the decision using a simple decision tree method, where expectation, or expected value, was used to determine optimum decisions. Expected value is the probability-weighted average of the possible outcomes of an alternative in a decision problem (Clemen, 1996).

$$\text{Expected value of } X = x_1 P(X = x_1) + x_2 P(X = x_2) + \ldots + x_n P(X = x_n)$$

$$= \sum_{i=1}^{n} x_i P(X = x_i).$$

## B. THE DECISION CONTEXT

The challenge of discovering and selecting an operational decision for analysis was noteworthy. Surprisingly, even with all the decisions made daily throughout the DoD, it proved difficult to identify a decision context that was suitable for this study. We were looking for an operational problem that met several criteria:

- Operation is sensitive to a weather parameter that is well forecast;
- Decision alternatives exist;
- Expected weather is sometimes the deciding factor;
- Forecast information is available at lead times when decisions are made;
- We had some insight into alternatives, lead times, and consequences.

The critical environmental parameter also would ideally be available in multiple forecast forms i.e., climatology, deterministic, and ensemble prediction.

The decision context chosen was an ammunition offload from an aircraft carrier (CVN) returning from a Western Pacific deployment. A CVN returning to homeport must cross-deck its ammunition while underway to a support ship. This common operation occurs with every return from deployment.

The actual decision context for this evolution may vary from case to case, but there are always temporal, spatial, and environmental constraints. This study provides a simplified example decision context for an offload scenario, complete with objectives, constraints, alternatives, outcomes, consequences, and unfavorable weather conditions.

### 1. Scenario

The CVN is transiting across the Western Pacific, and the baseline scenario begins when the ship crosses 17.5°N, 150°E. It is following a great circle position of intended movement (PIM) to Pearl Harbor, HI (21.33°N, 158°W), where it will pull in to port to onload family and friends of shipboard personnel for a Tiger Cruise.

The ship's speed of advancement (SOA) is just over 12 knots, which is slightly adjustable, up to a maximum of 18 knots, to achieve westward progression of 5° longitude per day.

En route, the CVN must conduct an ammunition offload prior to crossing 180°; due to previous delays, there is only one day scheduled to complete the offload. The CVN is to rendezvous with the support ship and commence the evolution at 175°E. The baseline scenario begins with the CVN at a position five days prior to the anticipated start of the offload.

The objective for the decision maker is to minimize the expected distance between the CVN's position and Pearl Harbor and successfully complete the offload.

### 2. Modeled Constraints

Spatially, the CVN may conduct its offload on any line of latitude between and including 15°N and 25°N. These latitudes and the aforementioned longitudes determine the offload zone (OZ).

Temporally, the ship must keep its SOA under 18 knots, to ensure the remaining ships in the CSG are able to keep pace and minimize fuel use. Additionally, the ship must arrive in Pearl Harbor on time.

To conduct the offload, the wind speed cannot exceed 25 knots during the evolution. While the ship can endure winds in excess of 25 knots during the remainder of its transit, encountering these high winds in the OZ will cause a delay in the ammunition offload. The ship will receive a wind forecast every 24 hours until it is one day from the OZ. Figure 2 offers a depiction of the situation.

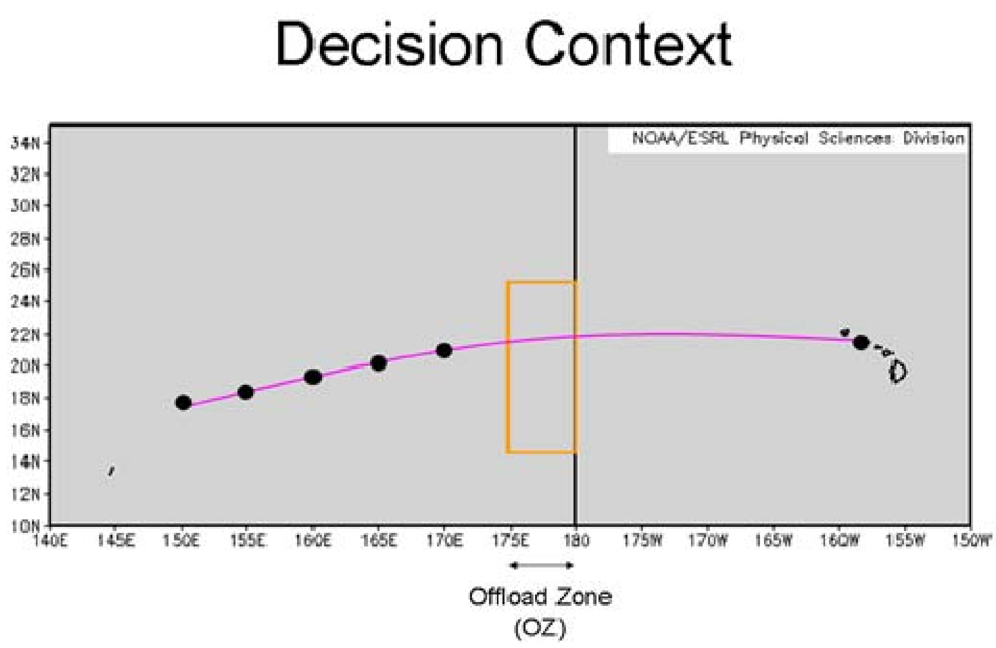


Figure 2. Decision context for CVN ammo offload. Planned PIM in pink, OZ in orange. Black dots represent time/location of wind forecast updates (adapted from Earth System Research Laboratory (ESRL), 2010).

### 3. Alternatives, Future States, and Consequences

The alternatives of the decision context are courses from the ship's current position at the time of each decision through transit lanes on each of the latitudes within the OZ with the courses continuing from the respective OZ transit lanes to Pearl Harbor. Alternatives of changing speeds prior to entering the OZ were also analyzed. Figure 3 illustrates the spatial course alternatives.

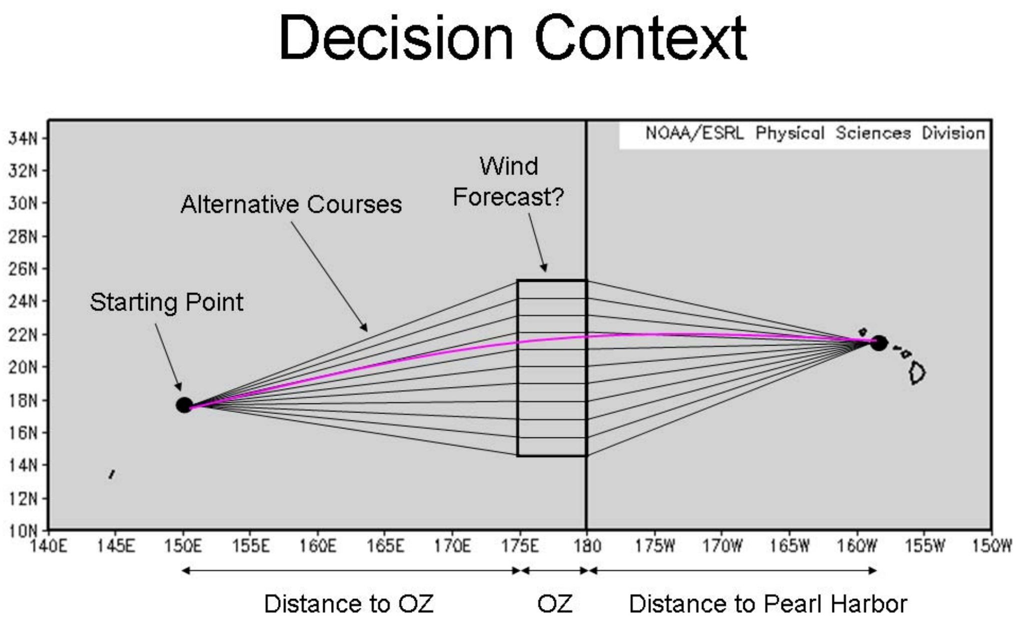


Figure 3. Spatial alternatives available to decision maker; original PIM in pink (adapted from ESRL, 2010).

The future states or possible outcomes of the decision are simply that the ship will or will not encounter winds above 25 knots in the OZ (Figure 4). To simulate the effect of a delay due to above threshold wind conditions, the future state of encountering such winds will include a distance penalty of 500 km, which is approximately one day of distance lost. A more severe consequence of 1000 km was also considered.

# Future States

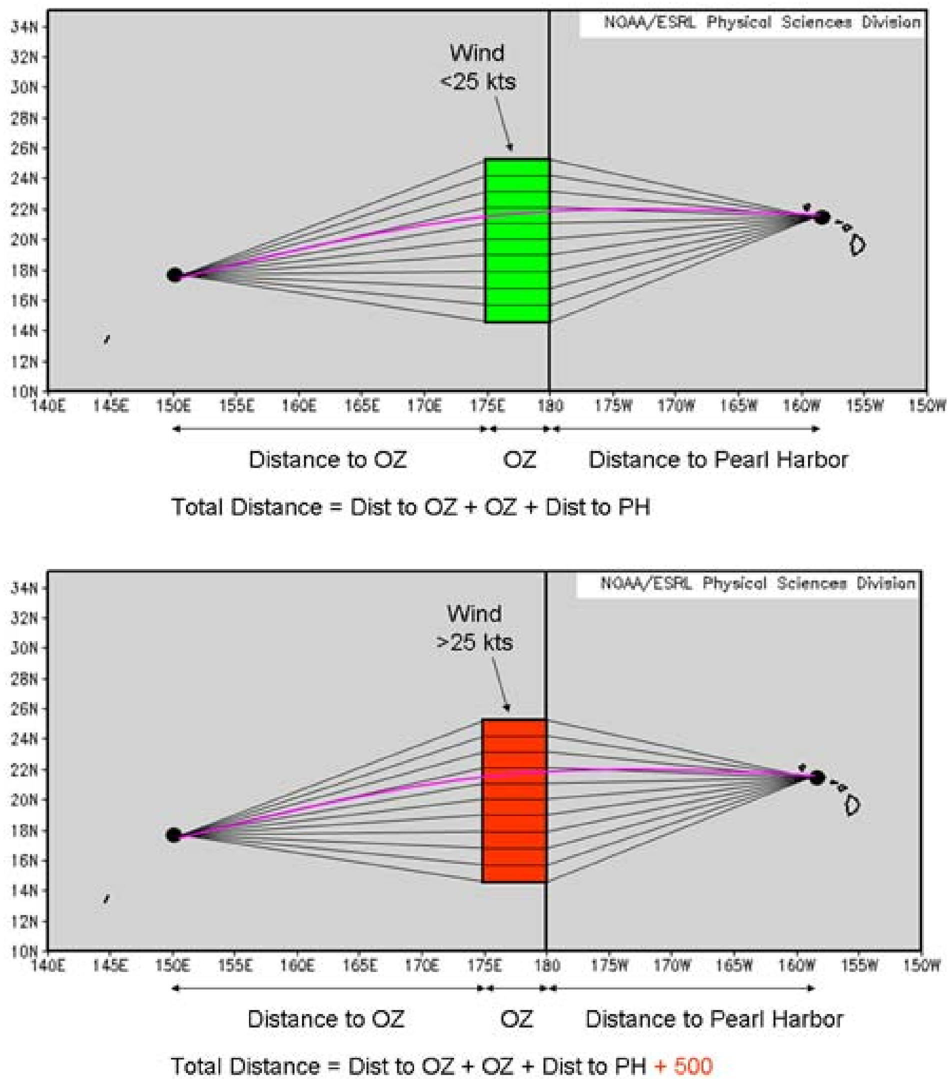


Figure 4. Future states of the decision: desired outcome (top) and unwanted outcome (bottom) (adapted from ESRL, 2010).

### 4. Solving the Decision Problem

To determine the optimum course to satisfy modeled objectives, the expected distance of each course alternative was calculated at each decision point. The necessary inputs were the distances of each above threshold and below threshold outcome for each alternative and the forecasted probability P of above threshold winds along each respective OZ lane, where $P_{PIM}$ indicates probability of exceeding threshold along the original PIM, and $P_{NC}$ is the probability of exceeding threshold along an alternate (new) course. A compressed decision tree and expected distance equations are shown in Figure 5.

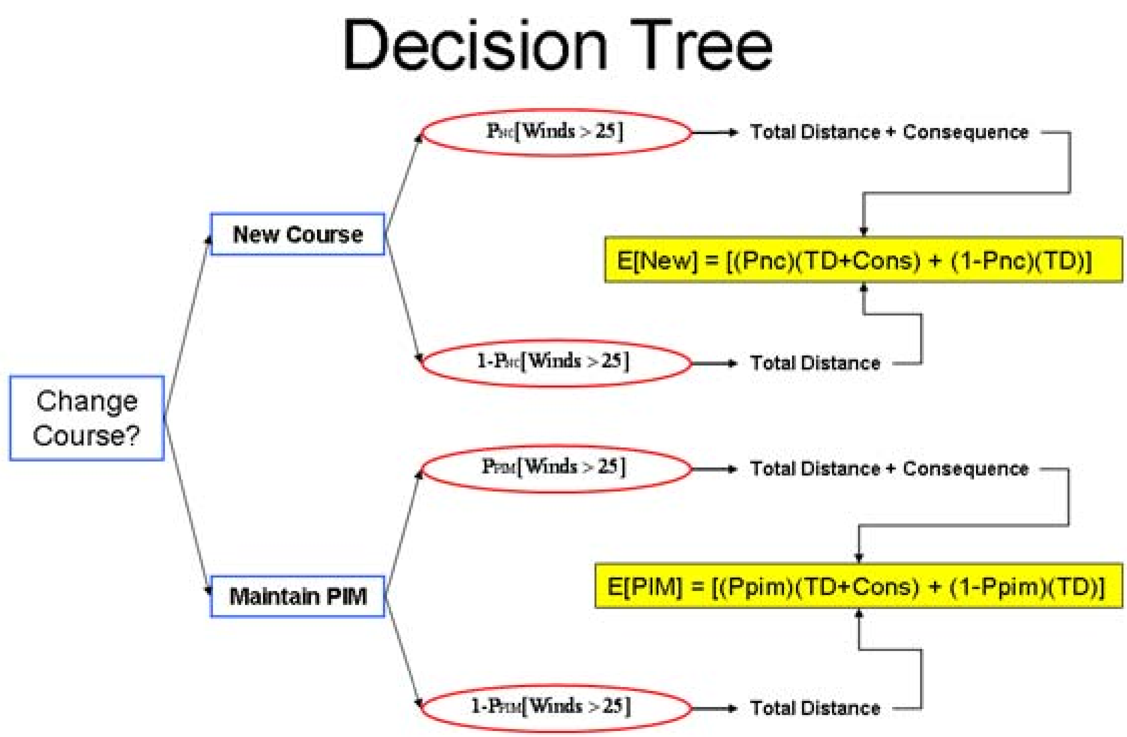


Figure 5. Decision tree for chosen decision context. Additional alternatives yield additional 'New Course' branches.

Once the expected distances of each alternative were determined, the optimum decision policy was to choose the alternative with the minimum expected distance. This process was repeated sequentially every 24 hours until the ship was one day from the OZ, where the final choice of transit lane was determined.

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# IV. CLIMATOLOGY

An examination of the climatology of winds in the region of interest was performed to understand the overall risk of encountering conditions above our modeled threshold, and also to identify the meteorological phenomena affecting the offload decision context. A characterization of the duration, intensity, size, movement, frequency, and timing of high-wind events was necessary to develop a set of decision alternatives appropriate to the decision problem facing the CVN.

## A. MEAN WINDS

Long-term means for surface winds give an initial indication of where and when the highest wind speeds occur. It is reasonable to start by considering the time and location of the highest mean wind speeds as indicative of the most frequent times and locations of above threshold wind events.

The Advanced Climate Analysis and Forecasting (ACAF) Web site allows for the retrieval and display of National Centers for Environmental Prediction (NCEP) reanalysis fields for monthly mean wind speeds from 1979–2008. Figure 6 shows the mean wind speeds for each month. There is only a slight variation in the mean winds from month to month and across the OZ region. From December to March, the northern portion of the OZ has mean wind speeds of 10 knots or less, while the southern portion of the OZ has mean wind speeds of 15-20 knots from April to July. The lowest mean winds across the entire OZ occur from August to October at 10–15 knots. The fact that this minimum occurs in the height of tropical cyclone season is a forceful reminder of the pitfalls of using mean values to characterize the environment. In the vicinity of the OZ, the monthly mean wind speed never exceeds 20 knots.

While the monthly mean wind data provide hints about when and where wind events greater than 25 knots may occur, more information about the distribution of the wind speeds around the mean was needed to accurately support optimized decisions.

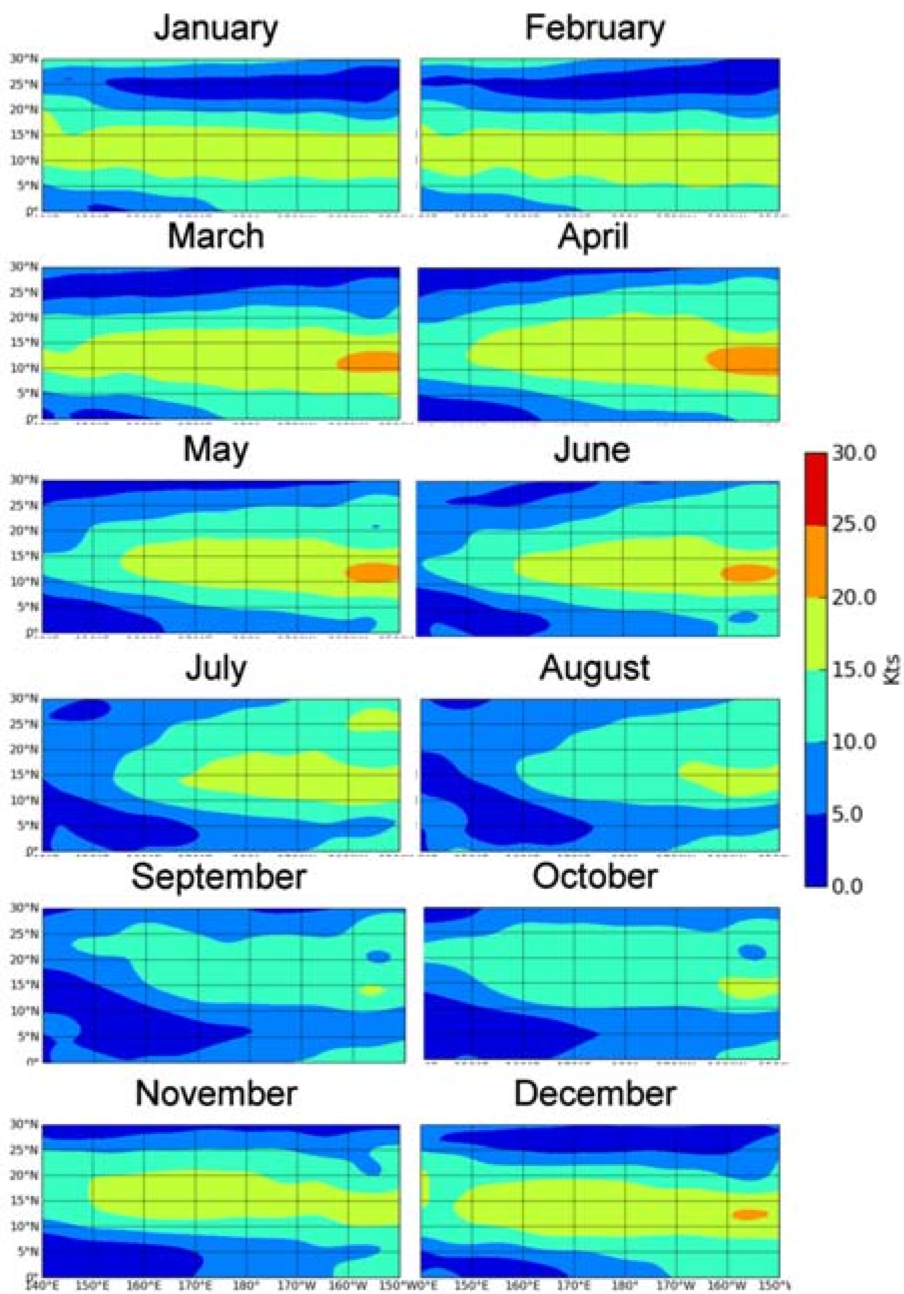


Figure 6. NCEP Reanalysis monthly mean wind speeds (ACAF, 2010). Central Pacific Ocean (0° - 30°N, 140°E - 150°W).

## B. FREQUENCIES OF OCCURRENCE

The same ACAF Web site also allows the user to identify a specific wind speed threshold and view the historical frequencies with which that threshold is exceeded. This statistical information provides a much clearer sense of the likelihood of encountering a high-wind event, at least climatologically.

Appendix A displays the frequencies of occurrence, by month, of wind speeds greater than 20 knots and 25 knots. Figure 7 shows the December frequencies of occurrence along with the example PIM and OZ. The most obvious characteristic of the frequency plots was the distinct reduction from the occurrence of 20 knot wind events to 25 knot events. Clearly, a 25 knot event is a rare happening, with near-zero probabilities near the OZ in all months. Further, from May through November, there is no evidence of wind speeds greater than 25 knots across the entire region pictured. (Even though we know tropical cyclone (TC) tracks occasionally affect this area, apparently the reanalysis fields do not contain enough TC-associated winds to show up in the 25 knot frequency of occurrence charts.) The 20 knot frequencies are higher during the winter months, steadily decreasing from spring to fall before increasing dramatically in November.

Because the NCEP reanalysis data that define the frequency distribution are not a continuous sample, it is possible that some shorter duration, above threshold events occurred during the period covered. The spatial resolution of the data may have also precluded the identification of some 25 knot winds. It is evident, however, that the winds have rarely exceeded our modeled operational threshold for the offload decision context.

December was the only month that exhibited a clear increase in the probability of exceeding 25 knots anywhere in the OZ. Because the great circle PIM transited the northern portion of the OZ and the increased probabilities were near the southern boundary, both the PIM and its adjacent alternative transit lanes show zero probability of encountering above threshold conditions. For long

range planning, this confirmed the planned PIM minimized expected distance when using climatological probabilities. There is no advantage gained by changing course when the probability on the shortest course is zero or near zero and/or the adjacent alternatives have equal probabilities.

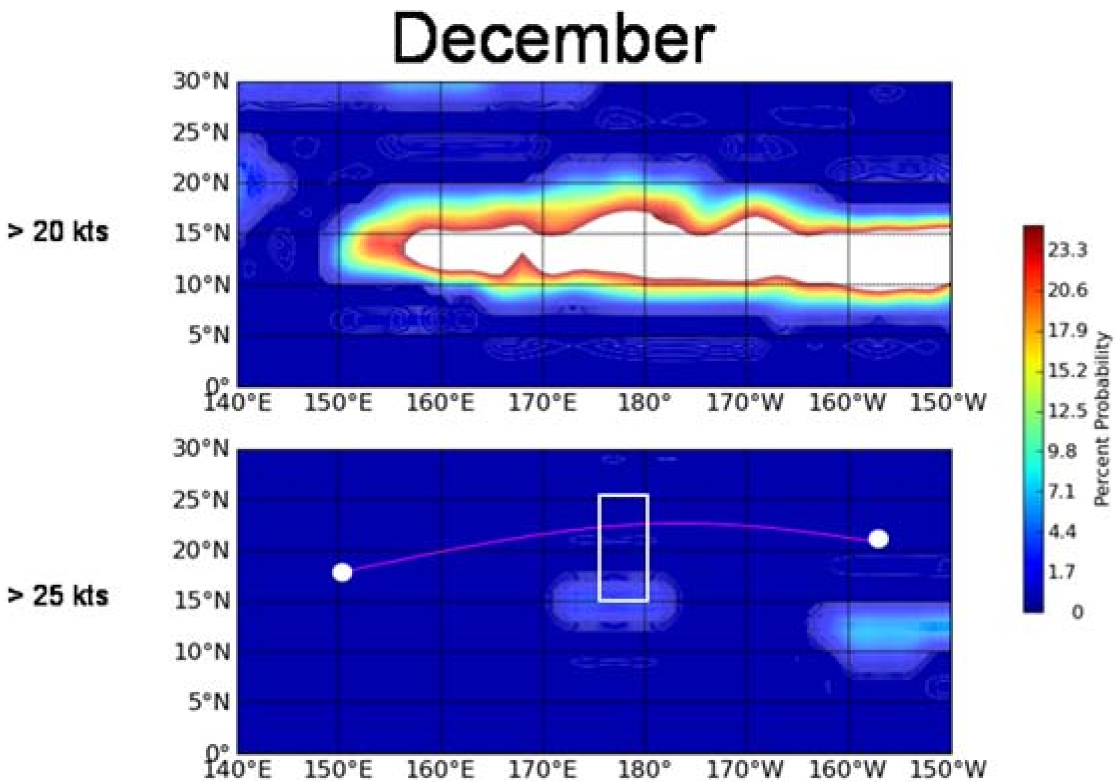


Figure 7. Historical frequency of exceeding 20 knot (top) and 25 knot (bottom) winds in December (adapted from ACAF, 2010).

## C. SUMMARY OF CLIMATOLOGY

While the long-term mean winds provided an awareness of the seasonal patterns of average wind speeds in the region of interest, they were insufficient for optimizing in the offload decision problem. The mean winds provided information about the likely location of the most conservative and most risky

routes, but because the stated objectives included more than just the successful completion of the offload, it was clear that some knowledge about the frequency distribution of the winds was necessary.

For the offload wind threshold of 25 knots, the data indicated a low historical frequency of occurrence in the OZ region, as well as in the surrounding North-central Pacific region. However, a significant rise in frequency was evident for a lower wind threshold of 20 knots. These historical probabilities would be useful for long-range planning to allow the decision makers to optimize their route using the best data available at the time. In the case of the offload decision scenario, the planned great circle PIM was the optimum course. Finally, future forecast probabilities would have to be sufficiently large, vary enough spatially across the alternatives, and come early enough in the decision cycle to deviate from the original PIM.

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# V. WIND EVENT CASES

Specific events from November through February 2000–2010 with wind speeds greater than 25 knots for durations of longer than one day were obtained from a manual search of the NCEP/NCAR reanalysis daily composite data from the NOAA ESRL Web site (ESRL 2010). The search focused in the area within or near the OZ and yielded only 23 such events. An additional search of April 2008–2010 produced one event.

Events were identified by assigning a maximum wind speed contour of 12.8 m/s (~25 knots) when plotting the surface vector wind parameter. Because of the manual nature of the search and use of daily mean winds to identify events, events with durations less than one day were not identified. In addition, a limited search into the summer months only produced wind events related to tropical cyclones.

Ultimately, three separate cases were chosen for detailed analysis. They were chosen because they differed in spatial orientation and extent, time of year, and because they occurred later in the search period, when more data were readily available. For these cases, we used the NCEP 6-hourly data to provide increased clarity of the onset, spatial extent, and other characteristics of the events. The events occurred in April 2008, January 2009, and November 2009. Appendix B contains the NCEP 6-hourly charts depicting these events. The January and November 2009 events were further analyzed within the offload decision context.

## A. APRIL 2008

The above threshold winds in the April 2008 case first entered the OZ on 13 April, 06Z, and some level of partial coverage existed over the OZ until 17 April, 12Z. The shape of above threshold winds was generally zonal and stretched from north of Hawaii westward as far as 160°E. The times of the

greatest OZ coverage were 14 April, 12Z; 15 April, 18Z; and 16 April, 18Z. The southernmost portion of the OZ remained below threshold conditions throughout the event. Figure 8 shows the wind speed distribution at 00Z on 14 April. The entire sequence is shown in Appendix B.

The likely cause of the high-wind event was an anomalously strong surface high pressure system in the NE Pacific (Figure 8). The presence of the easterly wind surge was supported by the increased pressure gradients associated with the anomalous high pressure system (Figure 8).

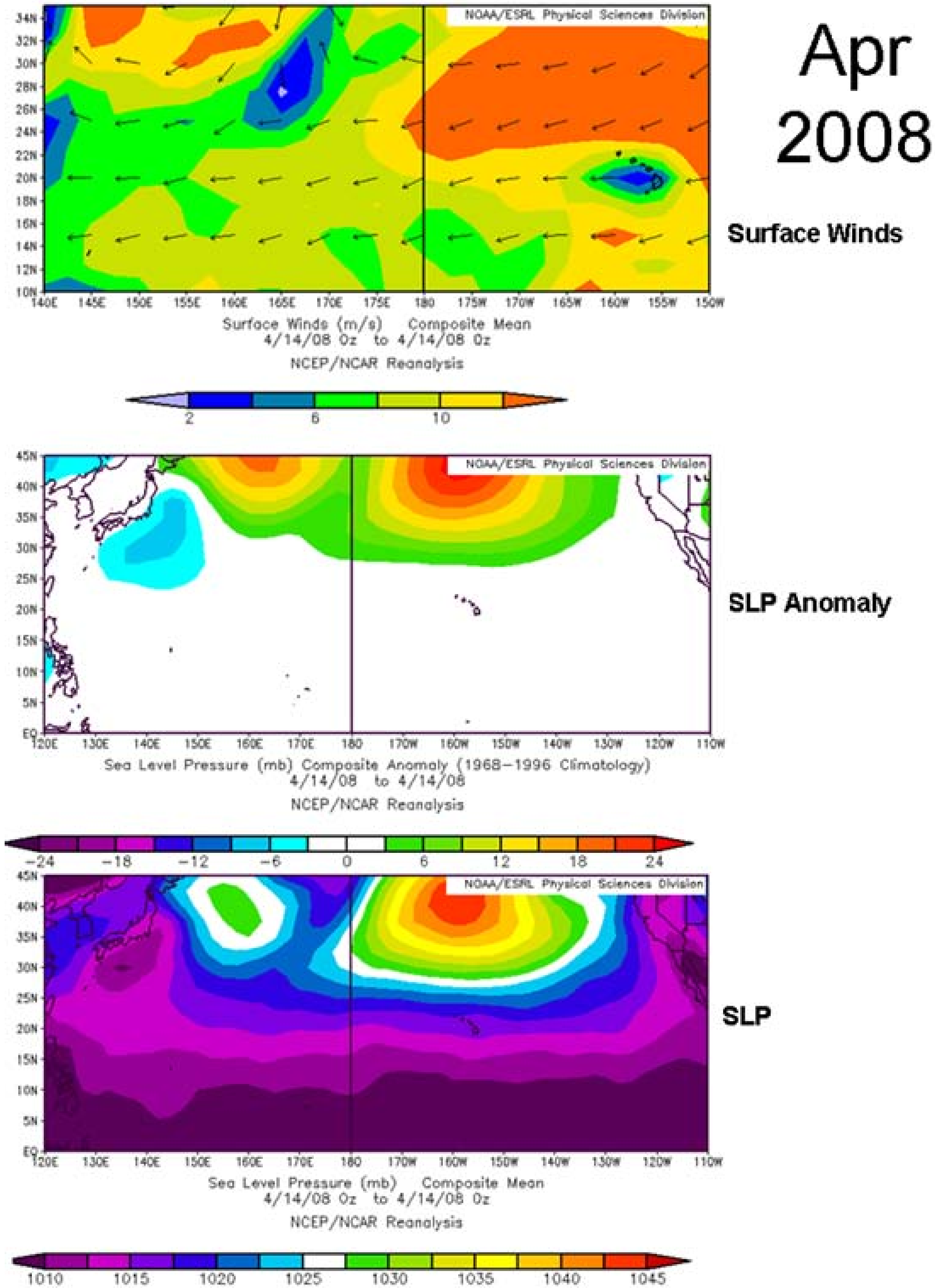


Figure 8. Surface winds (top), SLP anomaly (middle) and SLP (bottom) during the April 2008 wind event (ESRL, 2010). Note that the top panel is larger scale (smaller area) than the bottom two panels.

## B. JANUARY 2009

The January 2009 wind event began in the OZ as a northerly flow on 24 January, 06Z and maintained some level of coverage within the OZ through 28 January, 18Z. The flow steadily turned northeasterly as the event progressed, and the shape of the region bounded by the threshold contour varied throughout. Early in the event, the above threshold conditions were over the northern portion of the OZ with the southern portion below threshold. After the maximum and nearly complete coverage of the OZ on 25 January 12Z, the above threshold region steadily moved to cover the southern OZ with the northern OZ becoming below threshold. Figure 9 shows the wind speed distribution at 12Z on 25 January. The entire sequence is shown in Appendix B. As with the April 2008 event, anomalously strong surface high pressure in the NE Pacific was the likely cause of this event (Figure 9).

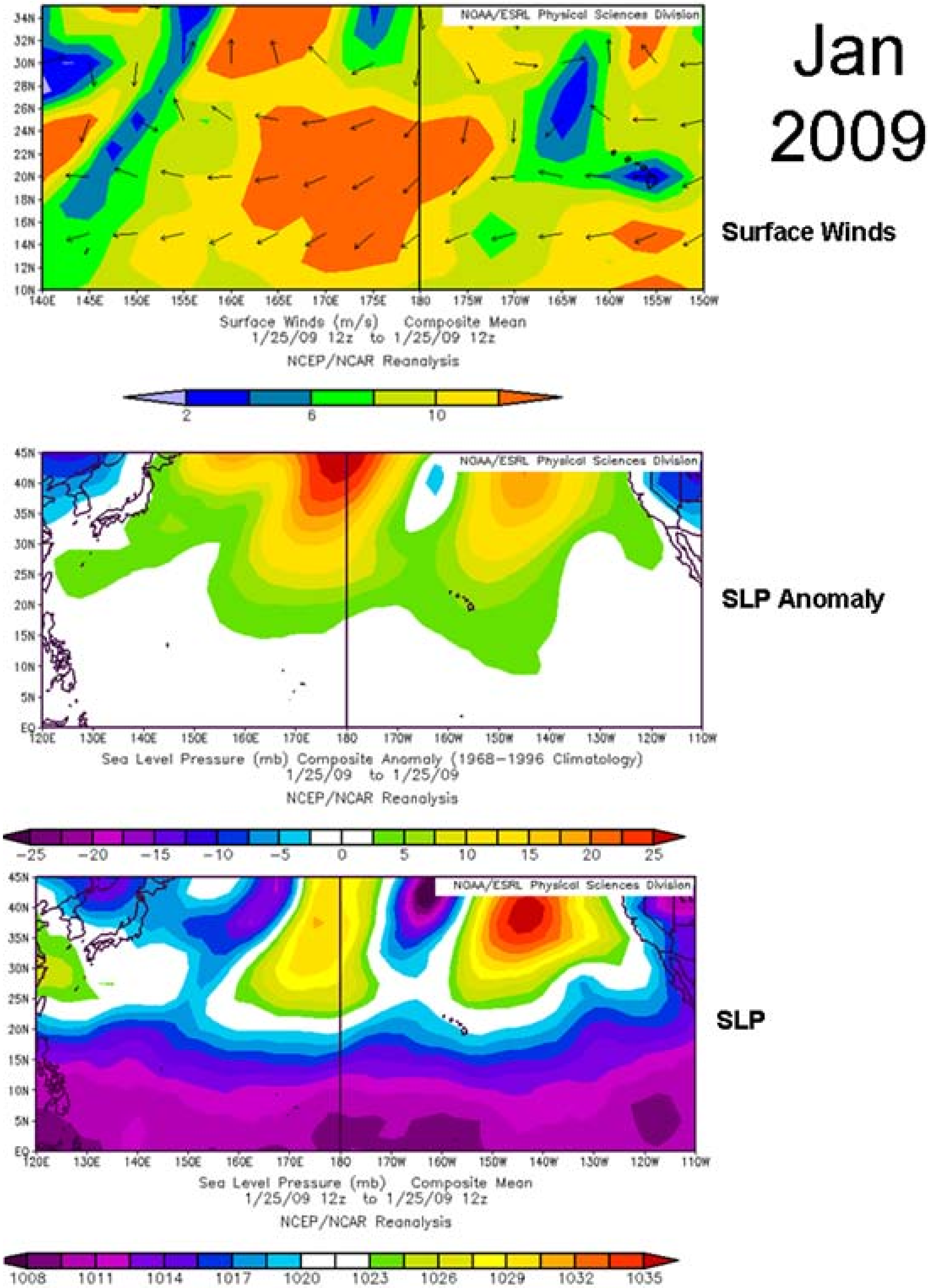


Figure 9. Surface winds (top), SLP anomaly (middle) and SLP (bottom) during the January 2009 wind event (ESRL, 2010). Note that the top panel is larger scale (smaller area) than the bottom two panels.

## C. NOVEMBER 2009

Above threshold winds first appeared near the southern edge of the OZ on 31 October, 18Z, with near threshold winds stretching well north and west of the OZ. By 1 Nov, 12Z, these near threshold winds strengthened and the entire OZ was above threshold. Complete coverage of the OZ persisted until early on 4 Nov, and partial coverage continued until late on 5 Nov. The flow was generally northeasterly to the east of 180° longitude, and turned easterly near the OZ. The size and shape of the region of high-winds varied, but this event was much larger than either the April 2008 or the January 2009 cases. Figure 10 shows the wind speed distribution at 00Z on 3 November. The entire sequence is shown in Appendix B.

Again, the cause of this event was an anomalously strong high pressure system, but this system was centered near 180° instead of the NE Pacific (Figure 10). Therefore, variation in the strength of the mid-Pacific low-level anticyclone appears to be a primary factor in forcing wind events that exceed the threshold over the OZ.

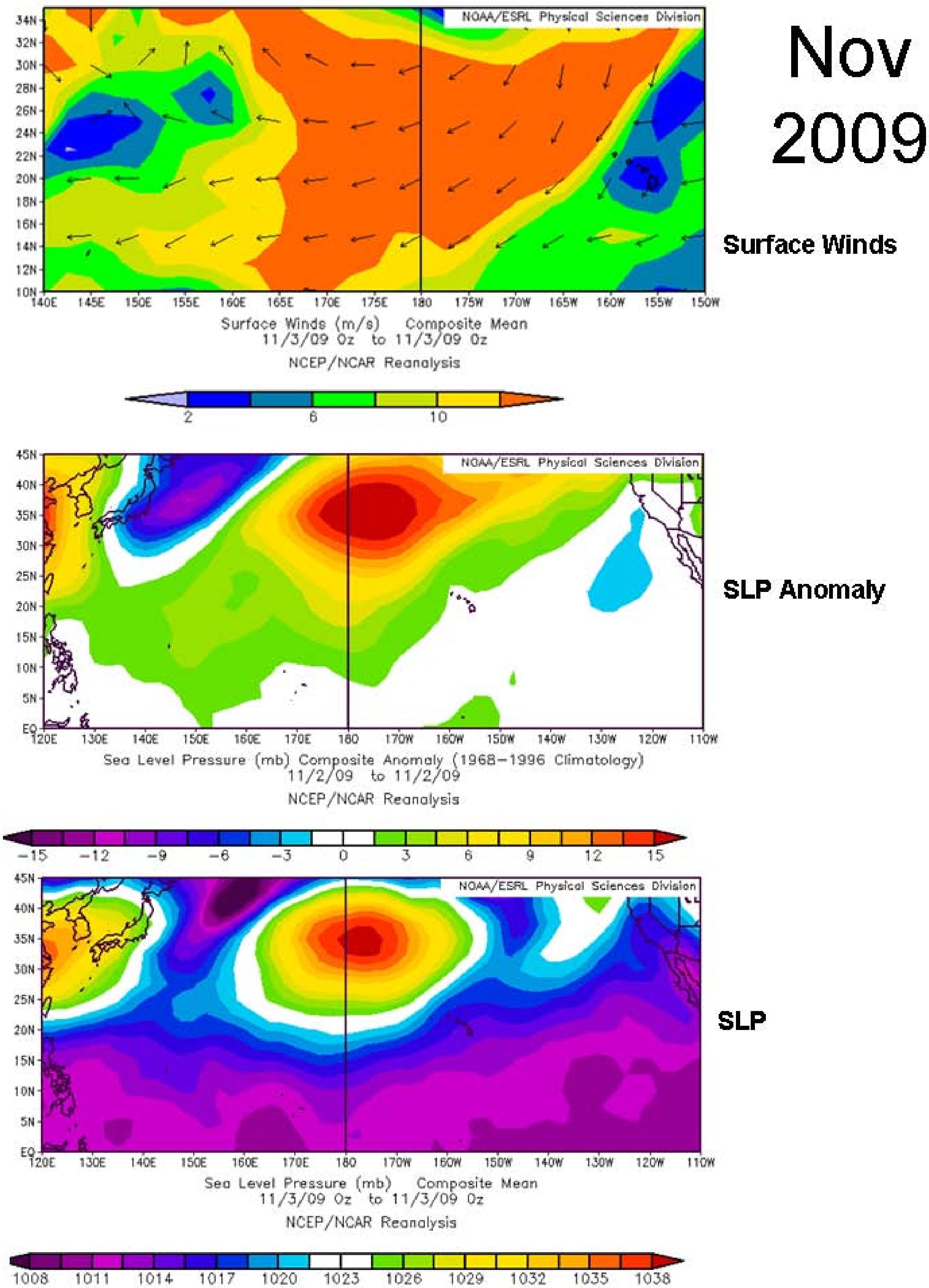


Figure 10. Surface winds (top), SLP anomaly (middle) and SLP (bottom) during the November 2009 wind event (ESRL, 2010). Note that the top panel is larger scale (smaller area) than the bottom two panels.

## D. SUMMARY OF WIND EVENT CASES

Although infrequent, wind events that exceed 25 knots and persist long enough to adversely affect an offload evolution have occurred. The three cases listed above had different characteristics, but all had a multiple day presence of above threshold winds in the OZ and were caused by anomalously strong high pressure systems over the North Pacific.

In the long-range planning phase, the available climatological information provided little indication of the possibility of these events. An update to that information would have been needed to provide warning to a CVN nearing the OZ. Operational NWP forecasts provide this type of information in a timeframe closer to the execution of an operation. Operational NWP forecasts for the January and November cases were examined within the offload decision context in an attempt to optimize the CVN's course.

# VI. ENSEMBLE PREDICTION

## A. ENSEMBLE DESCRIPTION

The European Centre for Medium-Range Weather Forecasts (ECMWF) Ensemble Prediction System (EPS) was the source of data used in the development of forecast probabilities of above threshold winds. The format of the data was Network Common Data Form (NetCDF), and it covered the periods prior to and through each of the January and November 2009 wind events.

At the time of the analyzed wind events, the ECMWF EPS was a global, 50 member ensemble. It had a spectral resolution of T399, which equated to approximately 50 km on a horizontal grid, and a vertical resolution of 62 levels in a hybrid sigma-pressure vertical coordinate system. The ECMWF used a perturbation technique based on singular vector decomposition to create perturbed analyses (European Centre for Medium-Range Weather Forecasts (ECMWF), 2010). The 10 m u- and v- wind velocities were examined, with forecasts from T0 to T180 in 12-hour increments. All members of the ensemble were available, and the spatial extent of the data was 140°E-150°W and 0° to 35°N.

## B. PROBABILITY MAPS

The magnitude of the wind speed from the u- and v- components were used to define a speed threshold of 12.8 m/s (~25 knots). The democratic voting method (J. Hacker, personal communication, 2010) was applied in a loop to count the number of members above the threshold at each grid point. More loops were applied to repeat this process for all initial and forecast times. This resulted in probability forecasts out to 180 hours in 12-hour increments for the valid times associated with each of the two wind events. Examples of these forecast probability maps are depicted in Appendix C.

## C. ALTERNATIVE TRACK PROBABILITY VALUES

The forecast problem for the decision scenario was complicated by the fact that the CVN would be transiting the OZ over the course of one day. This meant that a forecast accounting for the spatial and temporal variation of the ship's position within the OZ was desirable. The probability maps offered the opportunity to forecast the probability of above threshold winds at the entry, center, and exit of the OZ. These spatial locations were matched with corresponding forecast intervals for the ship's anticipated positions in the OZ.

To simulate realistic model forecast availability times, a 12-hour old model run was used for all forecasts. The means that the initial time of the NWP forecast was 12 hours before each decision time.

To simplify the decision process, but still account for the spatial and temporal variability in the probabilistic forecasts, the probability maps were used to create a single, summarized probability of exceeding the wind threshold at each alternative transit lane of the OZ. The summarized probability represented the highest probability forecast from the entry, center, and exit regions of the OZ for each latitude lane. This essentially amounted to a worst-case likelihood of encountering above threshold winds for each latitude alternative, meaning that, for example, if the probabilities were low for a particular latitude early in the OZ, but higher near the exit, only the higher probability would be utilized for decision-making.

Figure 11 summarizes the method employed to determine the maximum probability for each OZ transit lane. At each latitude lane and from the appropriate forecast field (T) for the entry of the OZ, the maximum of the probability values from grid points at 174°E—177°E was determined. The process was repeated for the next forecast (T+12 hours) for grid points from 176°E—179°E and 24 hours later (T+24 hours) from 178°E—179°W. The maximum of these three local probability maxima was the summarized probability

for that latitude lane. The result of this process was a singular, worst-case probability for each alternative latitude lane at each decision point.

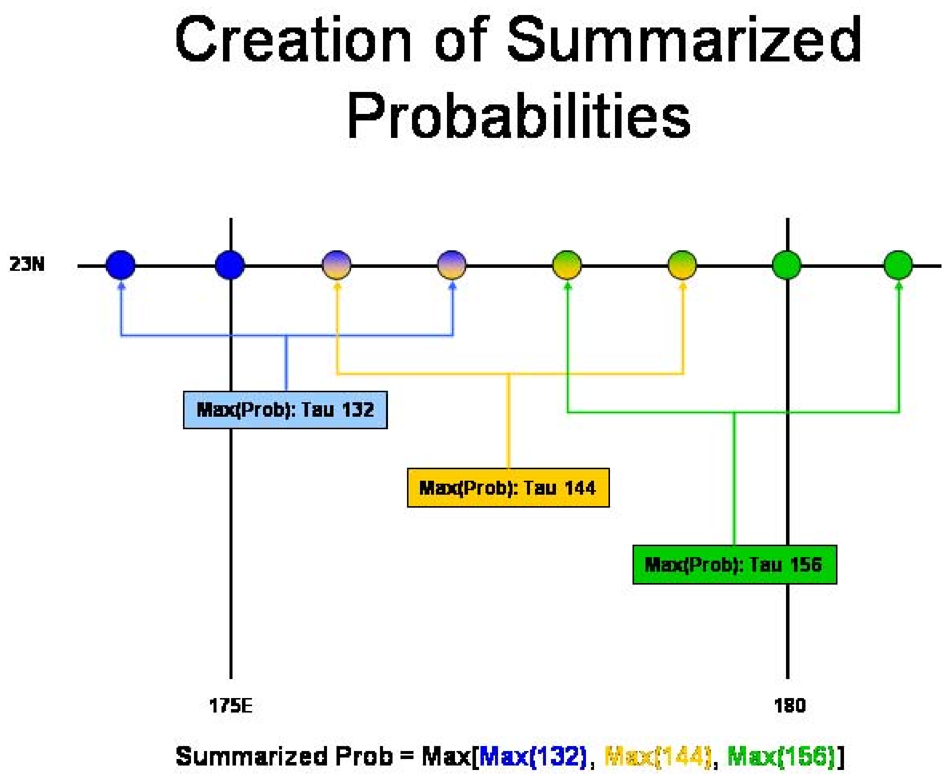


Figure 11. Method for creating summarized probabilities; represents a summarized probability for a 5-day lead time at a single latitude alternative.

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# VII. DECISION RECOMMENDATIONS AND OUTCOMES

For both the January and November 2009 wind event cases, several decision scenarios were analyzed (Figure 12). Each case begins with a basic, baseline scenario that places the CVN in the OZ at the approximate time of the spatial maximum of above threshold winds. The inclusion of forecast probabilities for course optimization begins five days prior to OZ entry. Forecasts and decisions are updated every 24 hours with the final forecast coming one day before OZ entry.

Other scenarios included cases with an earlier OZ entry date with lower probability of high winds, decisions to increase speed at the first decision point to enter the OZ a day earlier than planned, and cases where the forecast information was utilized beginning seven days prior to OZ entry.

In each of these scenarios, excluding the seven-day forecast, the decision problem was calculated with two different consequence values for encountering above threshold winds. This showed how changes in the decision context, independent of probabilistic information, affected the recommended or optimal alternatives.

## Decision Scenarios—January 2009
(Decisions updated every 24 hrs)

- Enter OZ on 25 Jan 12Z:
  - First decision point 5 days prior
  - Analyzed for 2 different consequence values
- Enter OZ on 23 Jan 12Z:
  - First decision point 5 days prior
  - Low forecasted probabilities
- Enter OZ on 24 Jan 12Z:
  - First decision point 4 days prior
  - Requires nominal SOA increase to arrive early
- Enter OZ on 25 Jan 12Z:
  - First decision point 7 days prior
  - Using the earliest available data

## Decision Scenarios—November 2009
(Decisions updated every 24 hrs)

- Enter OZ on 03 Nov 12Z:
  - First decision point 5 days prior
  - Analyzed for 2 different consequence values
- Enter OZ on 01 Nov 12Z:
  - First decision point 5 days prior
  - Shortly after onset of wind event
- Enter OZ on 02 Nov 12Z:
  - First decision point 4 days prior
  - Requires nominal SOA increase to arrive early
- Enter OZ on 03 Nov 12Z:
  - First decision point 7 days prior
  - Using the earliest available data

Figure 12. Decision scenarios for January and November 2009 wind event cases.

## A. COMPARISON OF PROBABILITIES AND EXPECTED VALUES

Because expected value is a function of probability, it was anticipated that the probability values would have an influence on the expected distance values. If the alternative with the minimum probability of above threshold winds was always the optimum decision from expectation calculations, then the expectation calculations would be unnecessary. A decision maker could simply choose the alternative with the lowest probability.

It is in situations when the optimum decision is an alternative that does not have the lowest probability that the expectation calculations become valuable. These are also the situations where a forecaster may need to be aware that the forecast alone does not provide enough information to make an optimum recommendation. In these cases, the other components of the decision context, e.g., the ship's position, track distances, and consequences, have more influence of the optimum decision.

### 1. January 2009

The scenarios for the January case included OZ entry dates of 23, 24, and 25 Jan, 12Z. The scenarios began at different initial decision times and included multiple consequence penalties. Figure 13 shows a summary of the relationship between probability of high winds and expected distance for the January scenarios.

Figure 13 indicates that for almost all the decision times analyzed, the optimum course, or course with the minimum expected distance, was also the course that had the lowest probability of above threshold winds in the OZ. Even in the cases where the minimum probability and minimum expected distance were not collocated, the optimum OZ latitude lane was within 2° latitude of the minimum probability.

Probability of High Winds vs.
Expected Distance

OZ Entry Date

| Tau → | 168 | | 144 | | 120 | | 96 | | 72 | | 48 | | 24 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conseq → | 500 | 1000 | 500 | 1000 | 500 | 1000 | 500 | 1000 | 500 | 1000 | 500 | 1000 | 500 | 1000 |
| 23_12Z | | | | | X | X | X | X | X | X | X | X | X | X |
| 24_12Z | | | | | | | X | X | X | X | X | X | X | X |
| 25_12Z | | | | | X | X | X | X | O | X | X | X | X | X |
| 25_12Z (7 Day) | O | | X | | X | | X | | O | | X | | X | |

X Minimum Probability, Minimum Expected Distance at same OZ latitude
O Minimum Probability, Minimum Expected Distance at different OZ latitude

Figure 13. Relationship of minimum probabilities to minimum expected distances at each decision point for January 2009 case.

Figure 14 is a plot of the probabilities and expected distance of the 25 Jan scenario at the 3-day decision point. It was notable that, although the minimum probability and minimum expected distance were at different latitudes, there were only slight differences in probability and expected distance from 23°N to 25°N, as compared to the significant increase in both probabilities and expected distance for the southern alternatives.

For the January 2009 case, it was evident that making decisions based on probabilities alone would have produced nearly the same outcome as performing expected distance calculations.

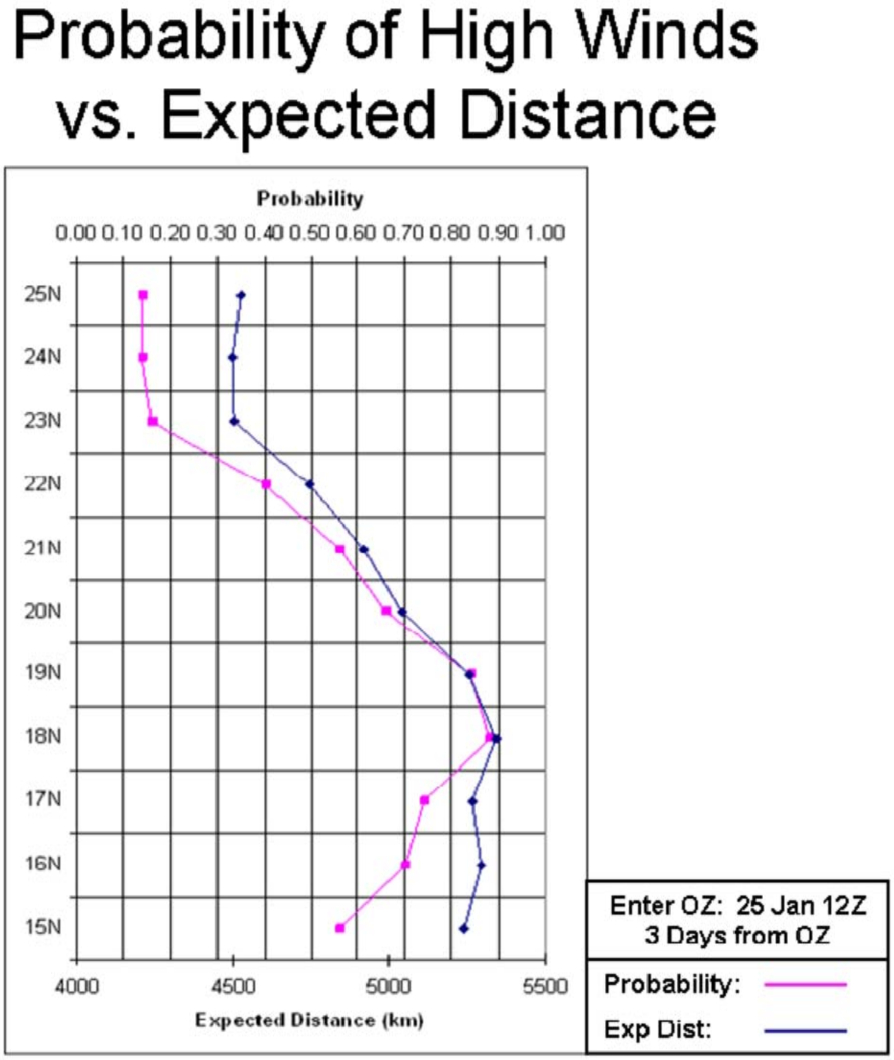


Figure 14. Comparison of probability and expected distance for course alternatives 3 days prior to OZ entry. Minimum expected distance through 23N (P = 0.16), minimum probability at 24N, 25N (P = 0.14).

### 2. November 2009

The scenarios for the November case included OZ entry dates of 1, 2, and 3 Nov, 12Z. The scenarios were identical to the January case, except in the time of the event itself. Figure 15 shows a summary of the relationship between probability of high winds and expected distance for the November scenarios.

The relationship between probability and expected distance was markedly different in the November case. For almost half the decision points in this scenario, the optimum choice was an alternative that was not the minimum probability. In fact, some of the optimum decisions were to proceed on an alternative that had a probability of 1.0, as the probabilities of the surrounding alternatives were not sufficiently low enough to reduce expected distance.

## Probability of High Winds vs. Expected Distance

| OZ Entry Date / Tau → | 168 | | 144 | | 120 | | 96 | | 72 | | 48 | | 24 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conseq → | 500 | 1000 | 500 | 1000 | 500 | 1000 | 500 | 1000 | 500 | 1000 | 500 | 1000 | 500 | 1000 |
| 01_12Z | | | | | O | O | O | O | O | X | X | X | O | X |
| 02_12Z | | | | | | | X | X | X | X | X | X | X | X |
| 03_12Z | | | | | O | X | O | X | O | X | O | X | X | O |
| 03_12Z (7 Day) | O | | O | | O | | O | | O | | O | | X | |

X Minimum Probability, Minimum Expected Distance at same OZ latitude

O Minimum Probability, Minimum Expected Distance at different OZ latitude

Figure 15. Relationship of minimum probabilities to minimum expected distances at each decision point for November 2009 case.

Figure 16 is a plot of the probabilities and expected distance of the 3 Nov scenario at the 3-day decision point. In this case, the minimum expected distance was for an alternative with a 100% probability forecast of winds exceeding the threshold. This exhibited that transiting to an alternative with a relatively lower probability forecast was too costly in distance for the benefit of the lower

probability. Interestingly, when the consequence penalty was doubled for this same scenario and decision time, the optimum choice was the alternative with the lowest probability. This showed the sensitivity of the optimal strategy to the consequence penalty.

For the November 2009 case, making decisions based on probabilities alone would have been quite costly in terms of the distance the ship would have traveled. Because the likelihood of encountering above threshold conditions throughout the OZ was consistently forecasted higher than in the January case, the optimization calculations tended to favor shorter courses. This indicated that if the ship were highly likely to encounter high winds on all alternatives, then the shortest course would limit the distance cost of a failed offload.

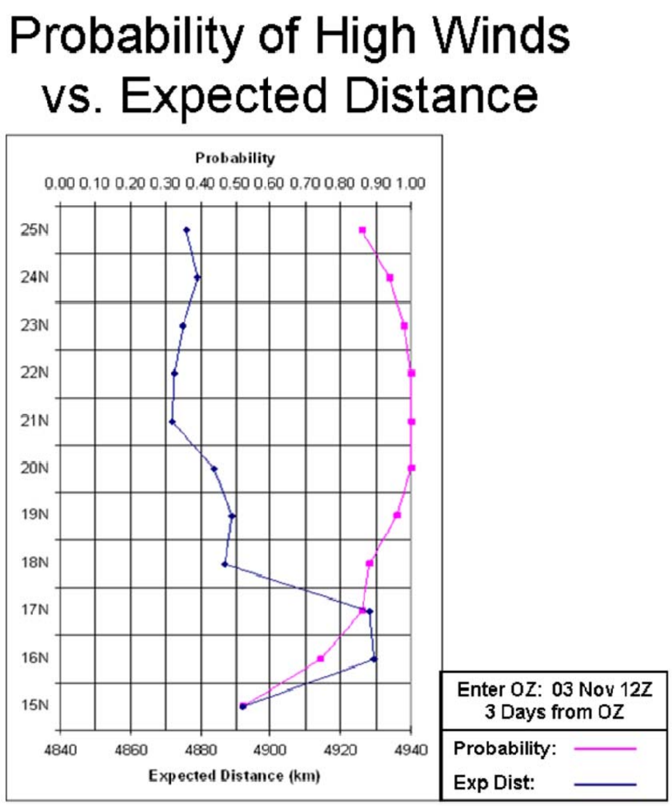


Figure 16. Comparison of probability and expected distance for course alternatives 3 days prior to OZ entry. Minimum expected distance through 21N (P = 1.00), minimum probability at 15N (P = 0.52).

## B. COMPARISON OF RECOMMENDATIONS AND OBSERVATIONS

The baseline scenarios for the January and November cases began identically, except for the forecast probabilities. Both used a 5-day lead time, 500 km consequence, and a starting position of 17.5°N, 150°E. Summarized probabilities of winds greater than 25 knots were assigned to the appropriate latitude lane in the OZ. Great circle distances for all alternative course segments were determined using a web-based application from Moveable Type, Ltd (Moveable Type, 2010).

The expectation equation was applied for each alternative to determine the OZ transit latitude associated with the minimum expected distance to Pearl Harbor. Once that latitude was known, the ship proceeded toward it. One day later, the ship's new position was determined along the course chosen at the first decision point, and its longitudinal position was rounded to 155°E. This rounding of the longitude was consistently performed at each new decision point to ensure the ship maintained 5° eastward progression each day, regardless of latitude. The rounding did not affect the total distances used in the calculation. The same process from the initial decision time was repeated daily from each new position and using the updated probability forecasts.

### 1. January 2009

For the January case, the chosen course at the first and second decision times was 25°N. At three days from the OZ, the first effect of the changing probability forecast was evident, as the ship turned toward 23°N, which was also chosen two days before the OZ.

One day prior to the planned OZ entry, two notable things occurred. First, the ship made one final turn to enter the OZ at 22°N. Second, because of the previous decisions, the ship was far enough to the north that the 15°N and 16°N transit lanes were dominated and unavailable as suitable alternatives. This meant that even if there were a 0% probability of above threshold conditions

forecasted at the two southernmost OZ lanes and a 100% chance of high winds at 22°N, the 22°N lane would have a lower expected distance.

Figures 17–18 depict the progression of the scenario, including a comparison to two Special Sensor Microwave Imager (SSMI) passes during the time the ship was in the OZ.

Several things were evident from this baseline scenario. The effect of updating the probability forecasts was seen in changes to the optimum course at new decision times. The effect of earlier decisions on later decisions was also apparent, especially in the case of the final decision having fewer alternatives.

Also notable was that even five days prior, the forecast probabilities provided a noticeable indication that an above threshold event could occur in the OZ. Given the rare nature of wind events of this magnitude, it was encouraging to see strikingly higher probabilities than the climatological frequency throughout the scenario. Appendix C contains probability maps for the 25 Jan, 12Z valid time. The final probability forecast compared favorably with the SSMI derived wind speeds, at least subjectively, with the higher probabilities seemingly aligned with the higher observed wind speeds.

Although this is a single case, the SSMI also allows for a loose evaluation of the actual outcome of the ship's offload evolution. The wind speed threshold of 12.8 m/s is marked in the last panel of Figure 18. The red areas of the SSMI are above threshold, the yellow areas are below threshold, and the orange areas are at or near threshold, depending on the shade of orange. These two snapshots of observed conditions indicate that the ship probably did encounter above threshold winds on its chosen OZ transit lane.

Finally, the distance traveled on the chosen course to the OZ was 2681 km. The distance the ship would have traveled from its initial position to the ultimate OZ entry point, 22°N, without the early forecasts was 2660 km.

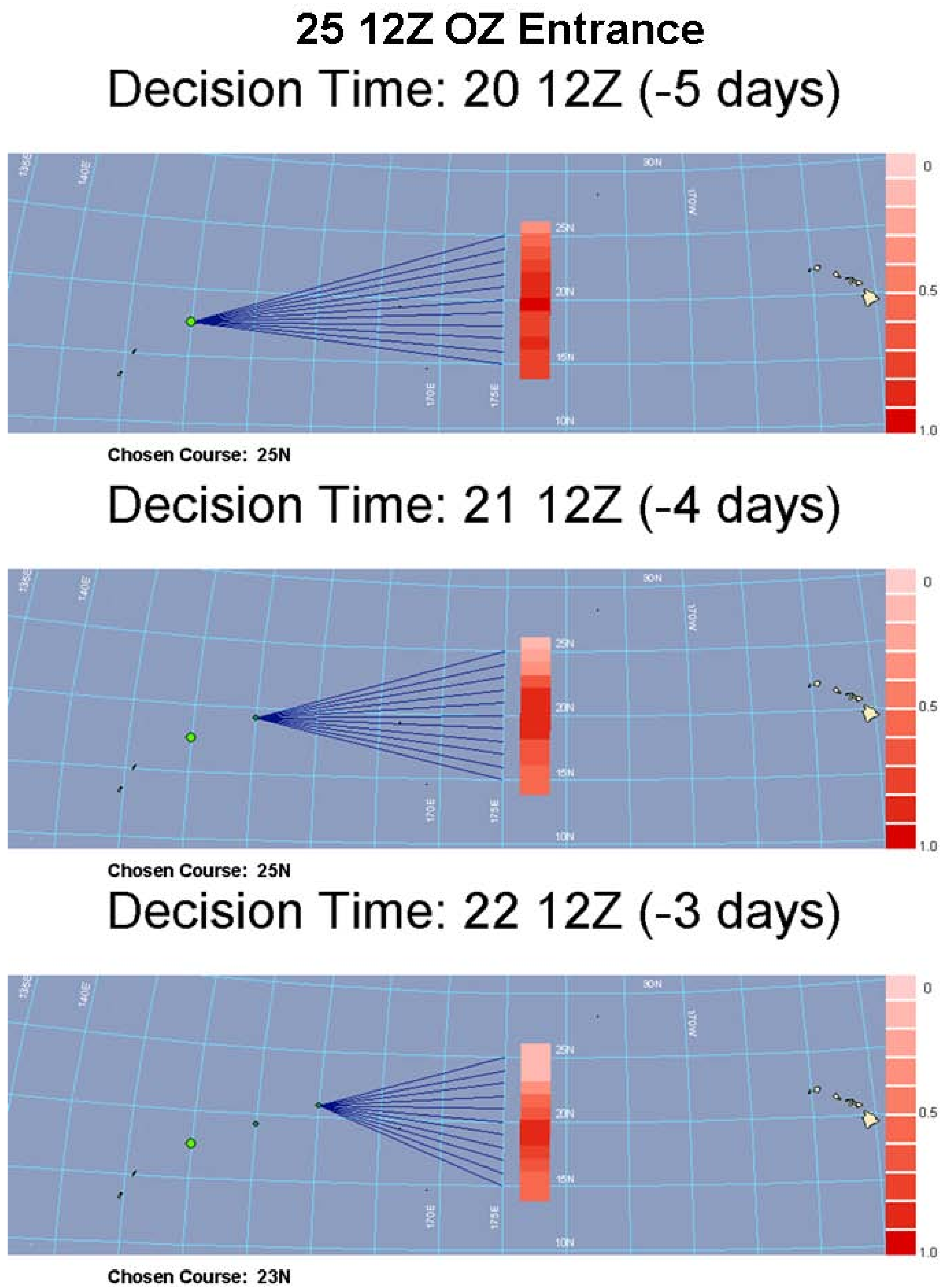


Figure 17. Course recommendations for 25 Jan OZ entry (500 consequence). Plotted using an equidistant conic projection; great circle routes are straight lines.

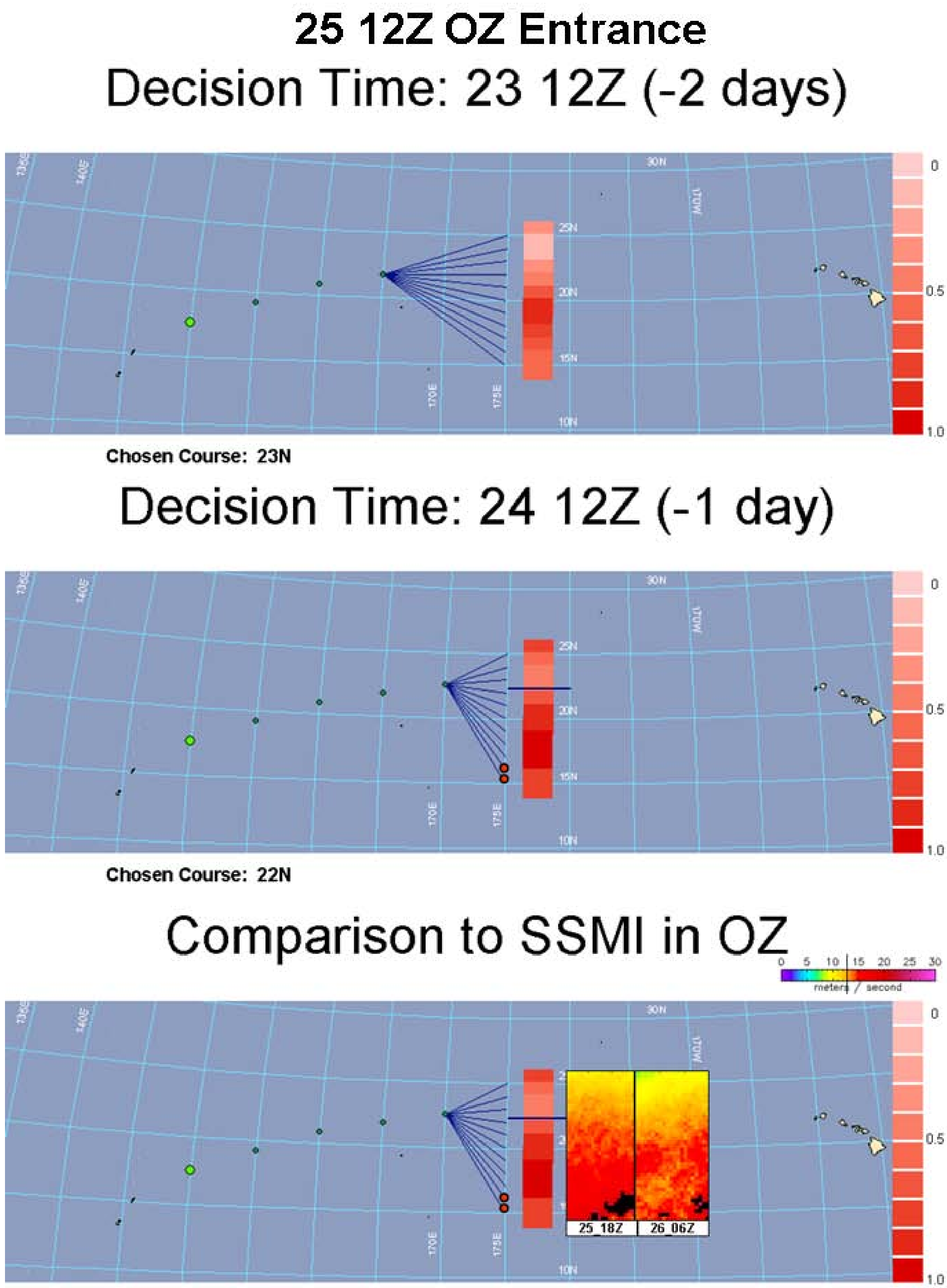


Figure 18. Course recommendations for 25 Jan OZ entry (500 consequence) and comparison to SSMI (Remote Sensing Systems (REMSS), 2010). Plotted using an equidistant conic projection; great circle routes are straight lines.

### 2. November 2009

For the November case, the chosen course on the first day was 16°N, followed by a major turn to 25°N the following day. The ship then turned back to the south toward 21°N for two days before finally choosing 25°N as its OZ entry point. Figures 19–20 show this scenario graphically.

The most striking difference between this case and the January case was the presence of 100% probabilities, which were first evident four days out. The number of alternatives having 100% probabilities increased with each forecast update. This agreement by all the ensemble members, with 50 of 50 predicting winds above 25 knots at these latitudes, was notable.

This case also differs in the major course changes made at each decision point. While the January case saw gradual progress toward the north, then incrementally back to the south, the November course moved south, then north, back to the south, before ultimately returning to a course that it had previously been following. These major course changes may cause a decision maker to lose confidence in the process.

From a forecast perspective, the existence of high probabilities from the onset of the scenario was impressive, as was the general increase in certainty of high winds with each successive forecast. However, this recognition of the likelihood of high winds did not seem to improve the decision outcomes.

In this case, the process of optimizing using the updating forecasts seemed only to make what would eventually be a bad outcome, even worse. The ship tracked back and forth in an attempt to find the shortest course, effectively lengthening its actual course at almost every decision point. It seemed that the decision context was suspect when the majority of the alternatives were forecasted to be in the undesirable future state with overwhelming certainty. Even though the turns were "optimum" in the mathematical sense, given the information available and considering only the modeled consequences (distance traveled plus distance penalty), they would not

seem optimum for actual ships and crews. They would likely perceive turning back and forth and then ultimately still being delayed by winds preventing the crossdeck evolution as worse than steaming straight ahead and being surprised by high winds.

Comparisons to SSMI in this case indicate that the ship probably had no chance of finding a course through the OZ that was not above the wind threshold. Again, the probability maps compare favorably with the available observational data.

Finally, the distance traveled on the chosen course to the OZ was 2867 km. The distance the ship would have traveled from its initial position to the ultimate OZ entry point, 25°N, without the early forecasts was 2717 km.

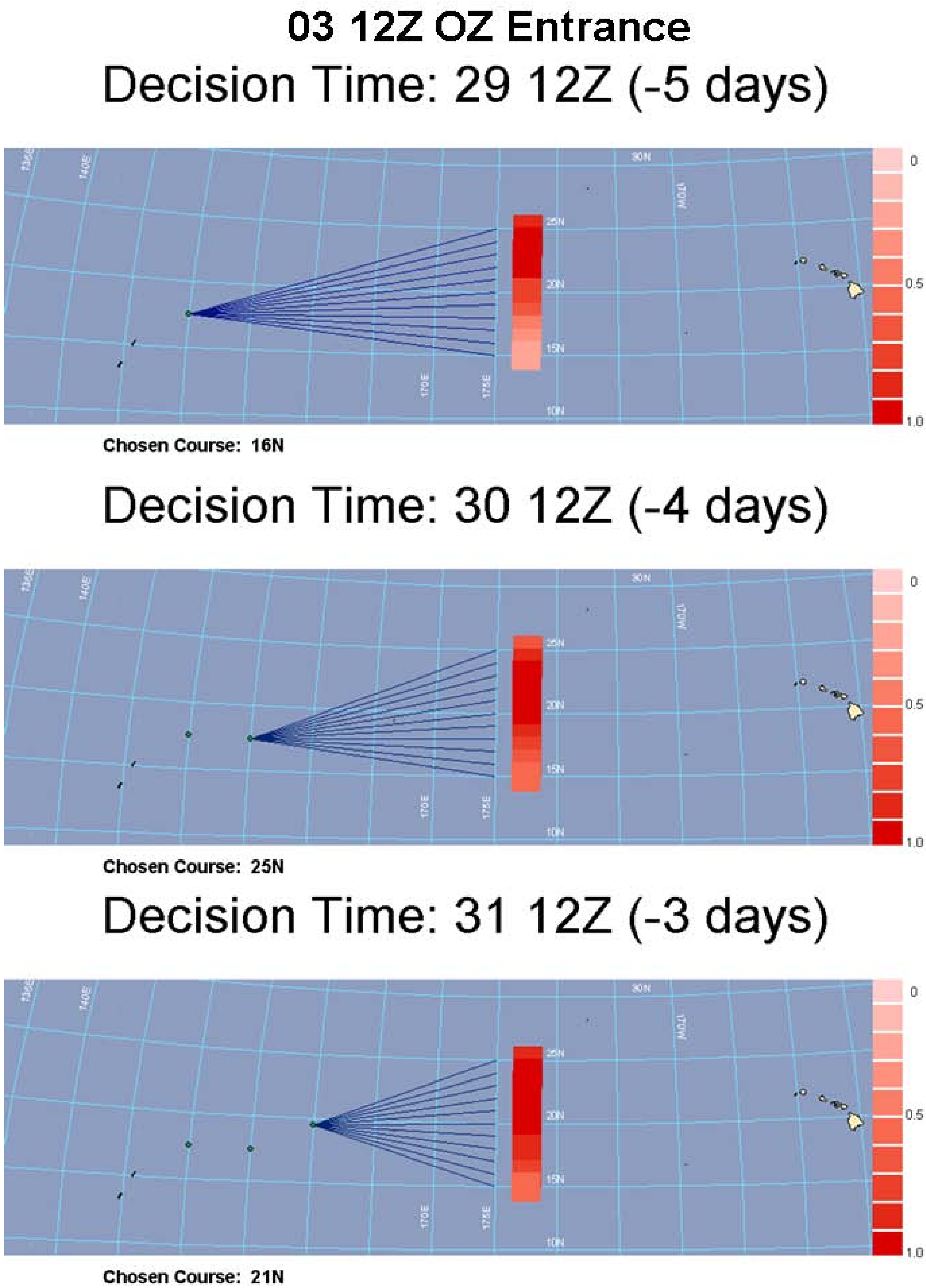


Figure 19. Course recommendations for 3 Nov OZ entry (500 consequence). Plotted using an equidistant conic projection; great circle routes are straight lines.

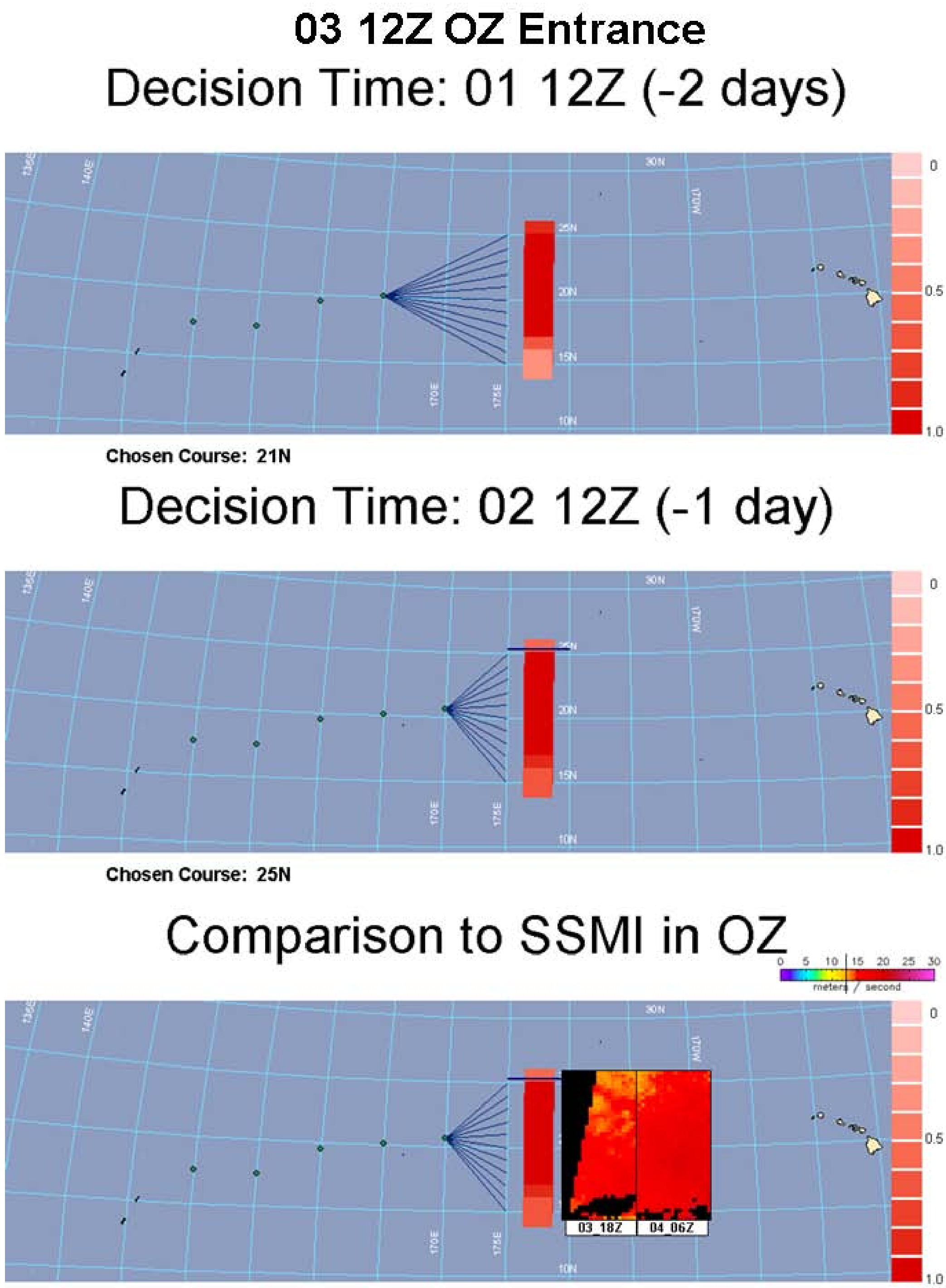


Figure 20. Course recommendations for 3 Nov OZ entry (500 consequence) and comparison to SSMI (REMSS, 2010). Plotted using an equidistant conic projection; great circle routes are straight lines.

### C. EFFECT OF CHANGING CONSEQUENCE PENALTY

A change to the consequence penalty used in the baseline scenarios was enacted to evaluate the effects of the same forecast inputs on different decision contexts or decision makers. The consequence penalties of both the January and November cases were doubled to 1000 km. All other initial characteristics of the scenarios remained constant.

Increasing the consequence of the undesirable outcome in the decision problem was akin to creating a more conservative, or safer, approach to making the decision. A more risk-adverse decision maker would coincide with a higher consequence penalty.

#### 1. January 2009

Figures 21–25 show the graphical comparison of the different decision contexts for the January case. The top image in each figure is the baseline scenario, and the bottom figure is the more conservative decision-making process.

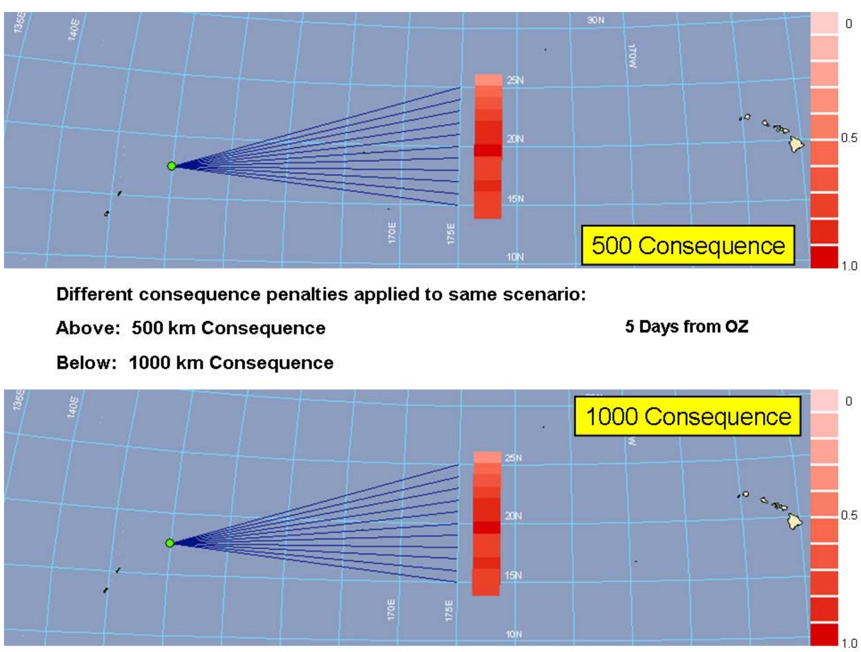


Figure 21. Comparison of different consequence values for encountering high winds. January 2009 case, 5 days from OZ.

Both decision makers choose the same course, 25°N, on the first two days (Figures 21, 22).

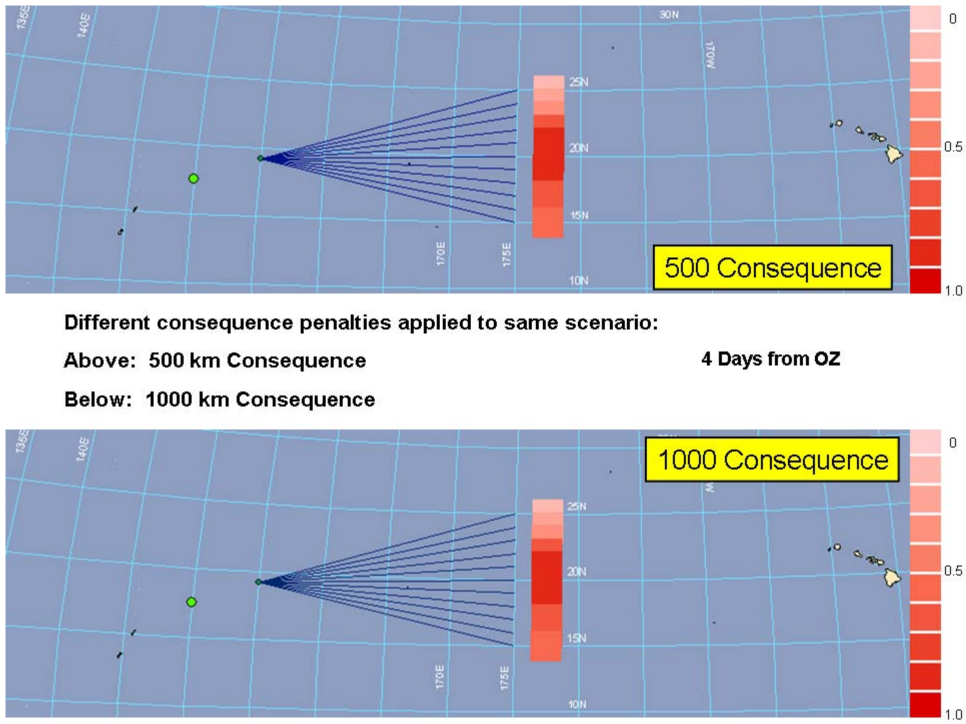


Figure 22. Comparison of different consequence values for encountering high winds. January 2009 case, 4 days from OZ.

The only difference between these scenarios came three days prior to the OZ (Figure 23). The more aggressive decision maker turned south toward 23°N, while the more conservative decision maker opted for 24°N. The result of this was the conservative course being slightly north of its aggressive counterpart when next decision point occurred (Figure 24). However, at that time both chose the same OZ entry point, 23°N, and by the time of the final decision point, both were in the same spatial position once again. Both chose 22°N as the OZ entry latitude (Figure 25).

Figure 25 also shows that, unlike the baseline scenario, the 1000 km consequence scenario has all course alternatives in play at the time of the final decision. Due to the increase of consequence in the expectation calculations,

the southernmost alternatives are no longer dominated. The conservative decision maker is more willing to take the long way around to avoid adverse conditions.

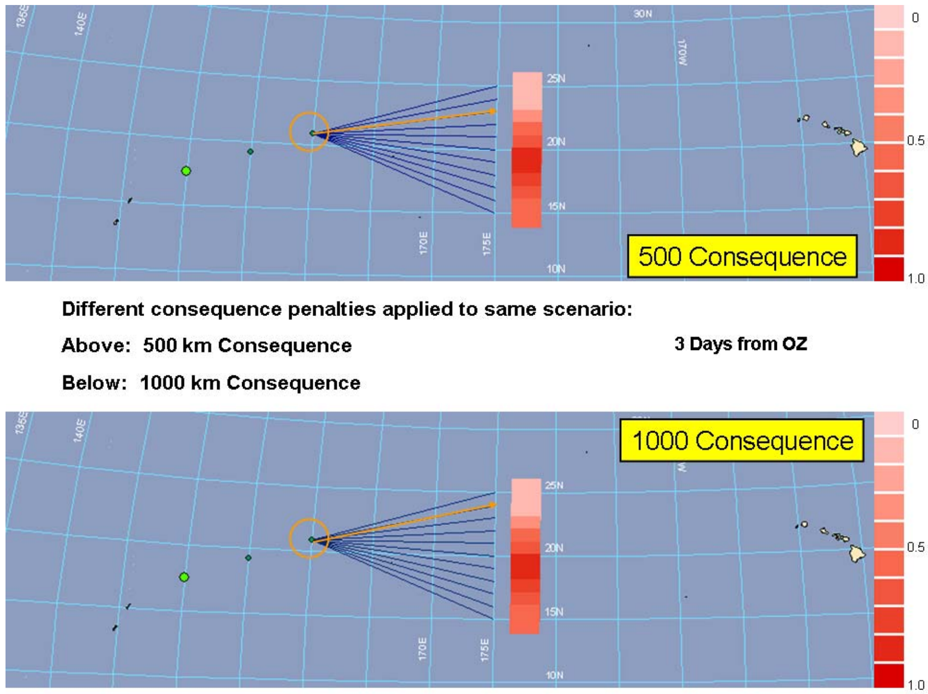


Figure 23. Comparison of different consequence values for encountering high winds. January 2009 case, 3 days from OZ.

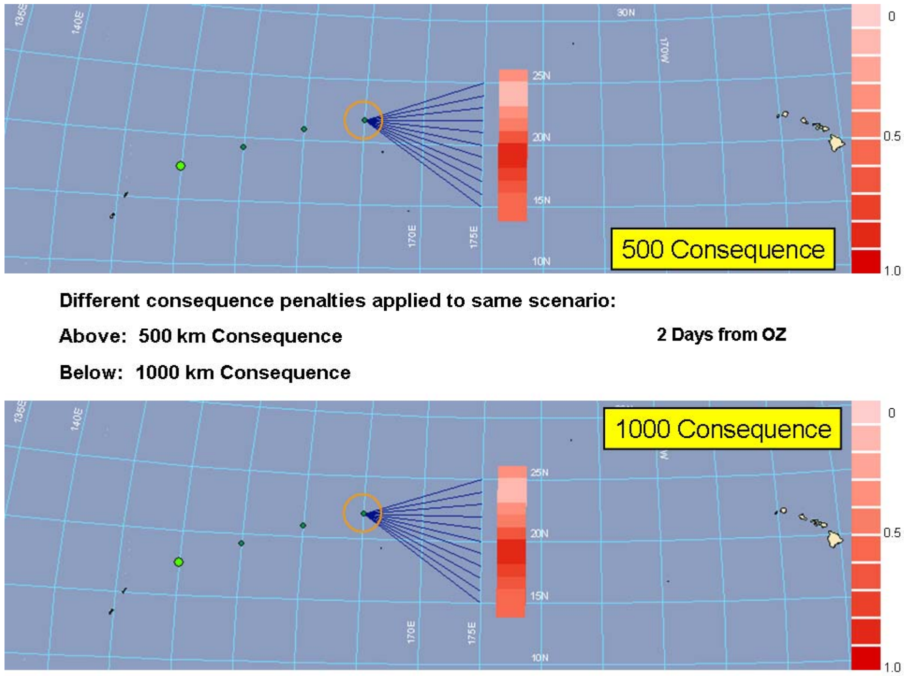


Figure 24. Comparison of different consequence values for encountering high winds. January 2009 case, 2 days from OZ.

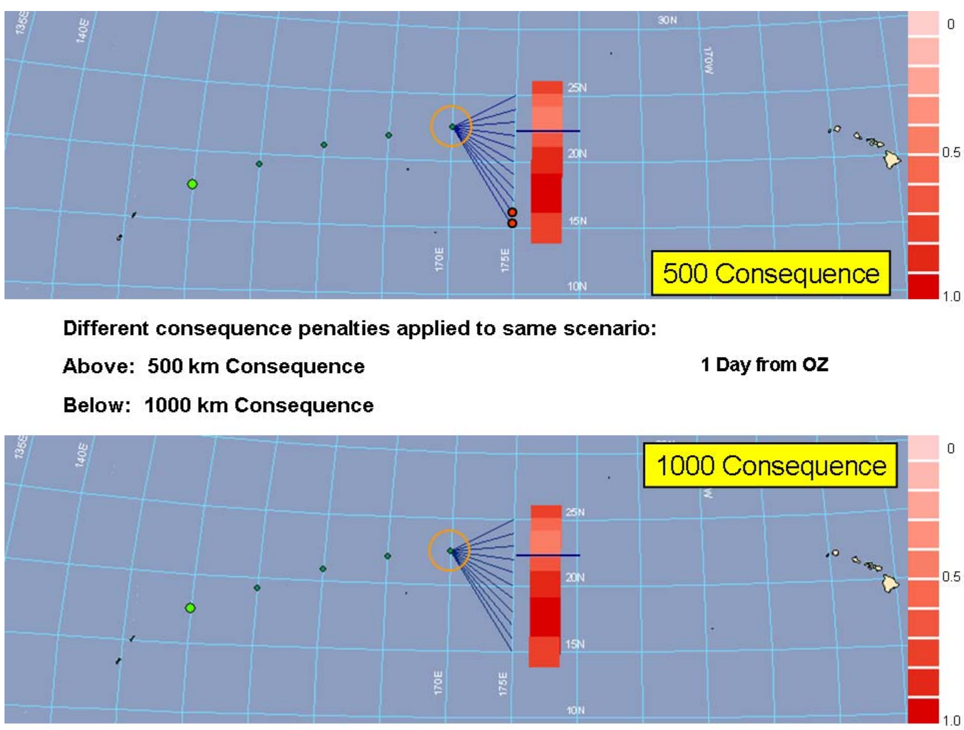


Figure 25. Comparison of different consequence values for encountering high winds. January 2009 case, 1 day from OZ.

### 2. November 2009

While only a small difference in overall course was caused by changing the consequence in the January case, the November case revealed a much larger effect. At the initial decision point, the optimum course for the 500 km consequence is 16°N, while the 1000 km course starts toward 15°N. It was shown previously that the 500 km consequence November scenario took an erratic route to the OZ. Conversely, the 1000 km consequence scenario yielded 15°N as its optimum course at every decision point (Figures 26-30).

While it was not evident in the January case, the November scenarios showed the more conservative decision maker was not as likely to make a major course change, resulting in a more consistent overall course.

In the January case, both decision makers ended up entering the OZ at the same latitude. In the November case, they enter at opposite ends of the OZ.

Finally, because both consequence scenarios proceeded toward the fringes of the spatial alternatives, their available alternatives are reduced at the final decision point (Figure 30). While these alternatives are not dominated as in the earlier example, the distances from the ships' locations to these OZ entry points are such that they cannot be reached in one day without exceeding the SOA limitation of 18 knots.

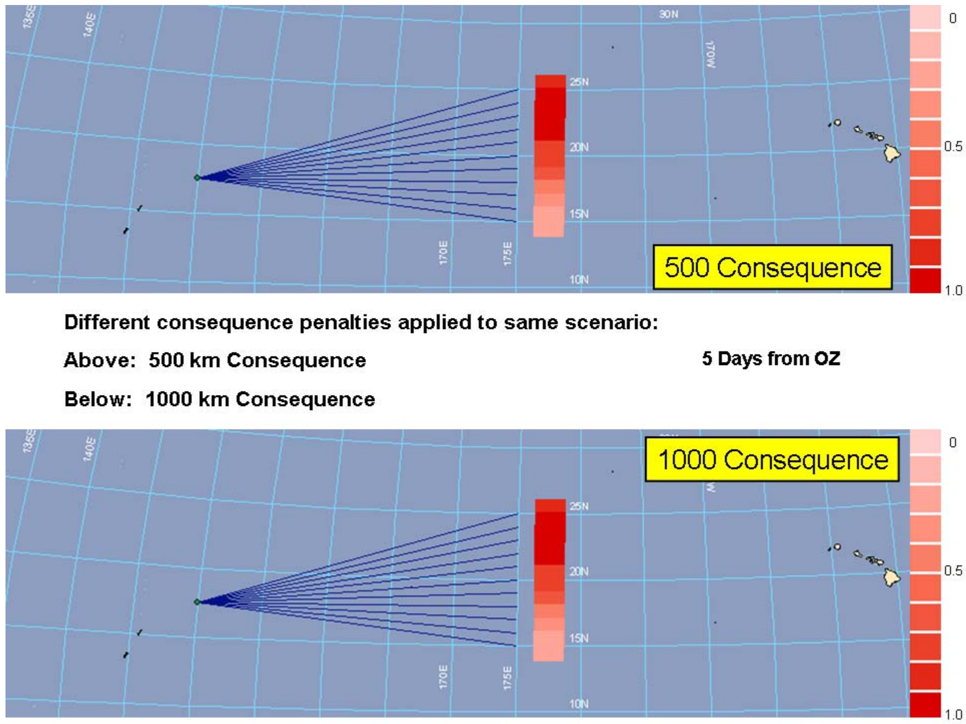


Figure 26. Comparison of different consequence values for encountering high winds. November 2009 case, 5 days from OZ.

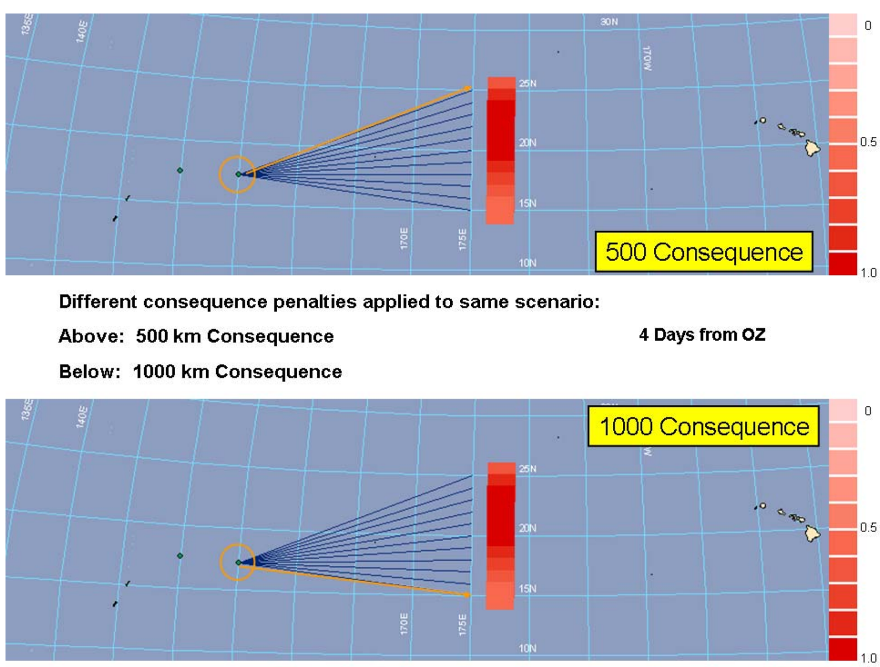


Figure 27. Comparison of different consequence values for encountering high winds. November 2009 case, 4 days from OZ.

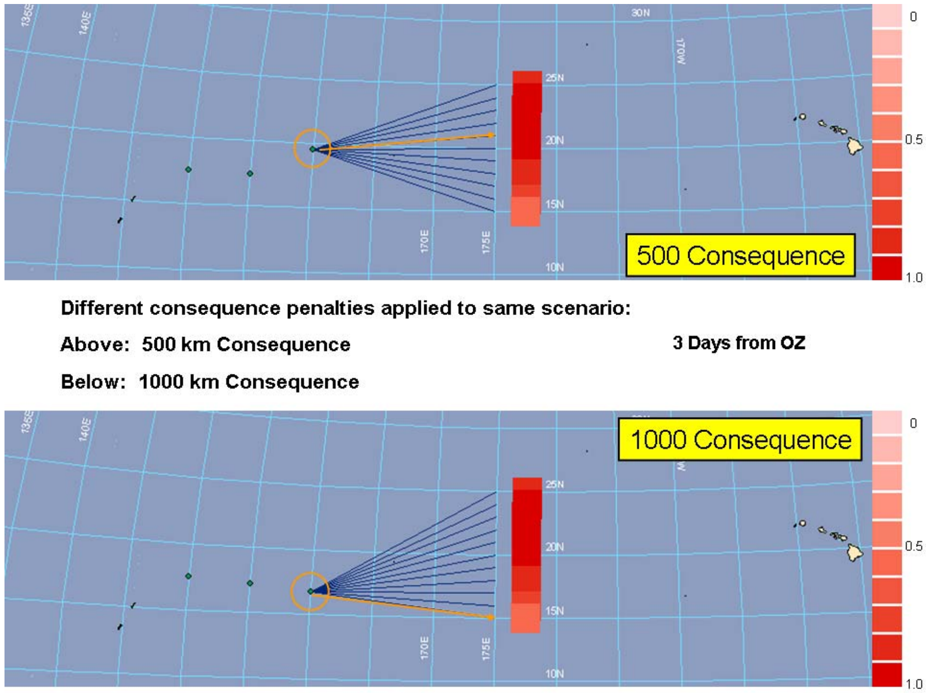


Figure 28. Comparison of different consequence values for encountering high winds. November 2009 case, 3 days from OZ.

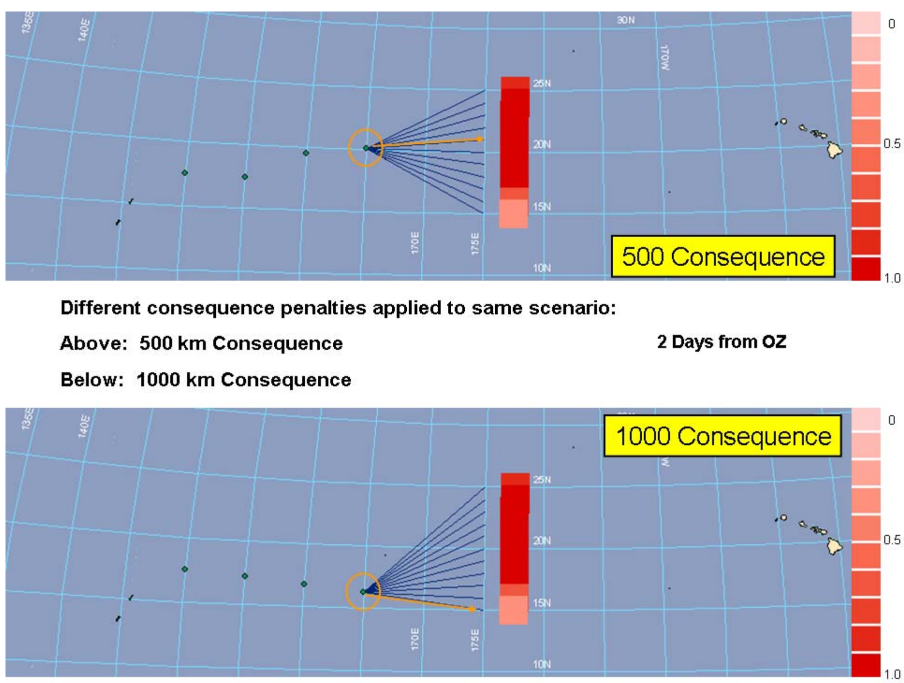


Figure 29. Comparison of different consequence values for encountering high winds. November 2009 case, 2 days from OZ.

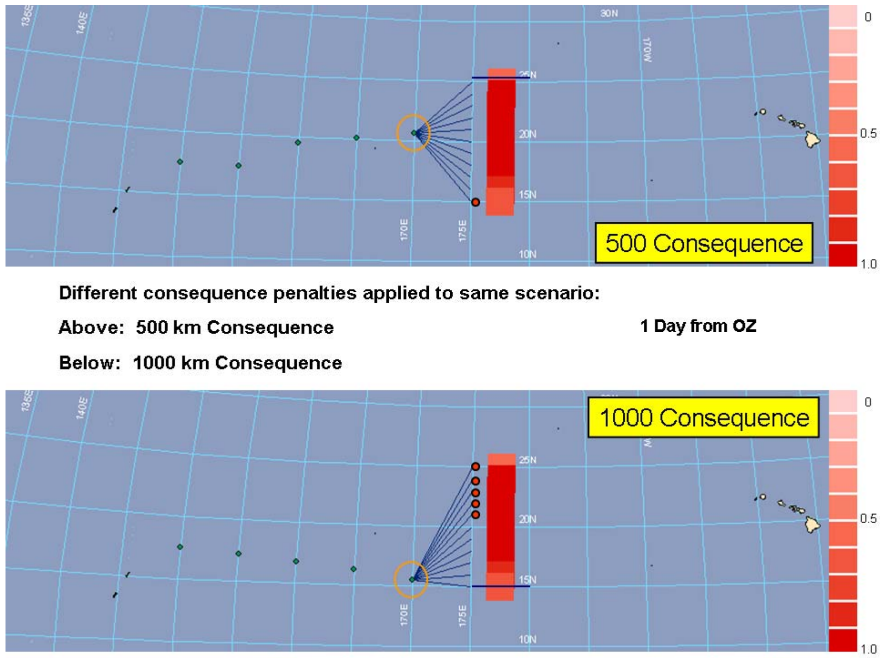


Figure 30. Comparison of different consequence values for encountering high winds. November 2009 case, 1 day from OZ.

## D. ALTERNATIVE OF SPEEDING UP FOR EARLY ARRIVAL

In the baseline scenarios for the wind event cases, the first decision point was five days prior to the planned OZ entry. Probability forecasts were provided and optimum routes were determined. Absent from these scenarios was the possibility that a CVN could arrive at the OZ early in the hopes of encountering more favorable conditions.

Because the ship is subject to SOA limitations, it would have to start increasing speed early enough in the decision cycle to maintain the viability of this alternative. In the scenarios that follow, the ship made its first decision at the same initial decision point. In this case, however, it had the option of choosing from the same alternative courses it had previously and the same spatial alternatives, but in only four days from the initial decision time. At the first decision point, the ship needed only a nominal SOA increase to approximately 14 knots to reach the OZ in four days. A speed increase was allowable, with no

penalty, up to 18 knots per the decision context. On the four day course, the ship maintained 6.25° of eastward progression per day, regardless of latitude.

The expectation calculations of the early arrival scenario were not adjusted to account for distance gained on the baseline scenario as time progressed. In other words, no advantage was given for early arrival, except in cases where early arrival resulted in higher probability of success.

### 1. January 2009

Figure 31 displays the probability forecasts and expected distances for all the alternatives available to the decision maker at the first decision point. The probability of above threshold conditions and the expected distances were forecasted to be lower at every OZ transit lane for a 24 January arrival, except at 16°N and 17°N. The optimum direction for either arrival was 25°N, which simplified the process, as the decision came down to steaming toward 25°N at 12 knots or 14 knots.

Because the expected distance of the early arrival alternative was less than that of the on-time arrival, the optimum decision was to increase speed and attempt to reach the OZ on 24 Jan, 12Z.

## Decision time: 20 Jan 12Z
## Forecasts for OZ:

**Enter OZ 25 Jan 12Z**

| Lat Lane | Prob | Expected Distance (km) |
|---|---|---|
| 25N | .40 | 5704 |
| 24N | .58 | 5766 |
| 23N | .68 | 5798 |
| 22N | .72 | 5809 |
| 21N | .80 | 5849 |
| 20N | .88 | 5899 |
| 19N | .90 | 5927 |
| 18N | .78 | 5895 |
| 17N | .76 | 5924 |
| 16N | .80 | 5990 |
| 15N | .76 | 6024 |

**Enter OZ 24 Jan 12Z**

| Lat Lane | Prob | Expected Distance (km) |
|---|---|---|
| 25N | .22 | 5614 |
| 24N | .34 | 5646 |
| 23N | .40 | 5658 |
| 22N | .48 | 5689 |
| 21N | .54 | 5719 |
| 20N | .64 | 5779 |
| 19N | .70 | 5827 |
| 18N | .76 | 5885 |
| 17N | .84 | 5964 |
| 16N | .82 | 6000 |
| 15N | .72 | 6004 |

Figure 31. Probability forecasts and expected distances of OZ transit alternatives for different arrival times—Jan 2009 wind event.

Figures 32–36 compare the baseline scenario with the early arrival scenario at each decision point. The most notable difference between the two scenarios was the disparity between their probability forecasts as time progressed, as the forecast for the early arrival was consistently more favorable.

After initially steaming toward 25°N, the early arrival ship turned toward 24°N at the second decision point and followed that course all the way to the OZ. As before, the ship from the baseline scenario had more course changes and entered the OZ at 22°N.

Figure 35 shows the baseline scenario ship two days from the OZ, where it faced an 18% probability of encountering high winds on its optimum transit lane. At the same time, the early arrival ship was one day from the OZ and the probability of high winds on its optimum course was 2%. At this point, if the baseline ship desired to increase its speed to enter the OZ on 24 January, it would have to increase its SOA to approximately 23 knots. Of course, this exceeded the maximum speed allowed in the decision context. Unfortunately, for the baseline ship, the probability forecast of its optimum track increased to 44% the following day.

Figure 36 displays the available SSMI for the times that each ship was in the OZ. As with the baseline scenario, the final probability forecast of the early arrival case compares favorably with the observed winds. Unlike the baseline scenario, however, it appears that the early arrival ship likely avoided above threshold conditions during its time in the OZ. Although the course taken by the early arrival ship appeared to be conservative relative to the first SSMI image, the onset of higher winds in the northern portion of the OZ is evident in the second SSMI image. This indicated that the inclusion of the later forecasts for the exit portion of the OZ in the development of the summarized probabilities influenced the ship's decision to enter the OZ at 24°N.

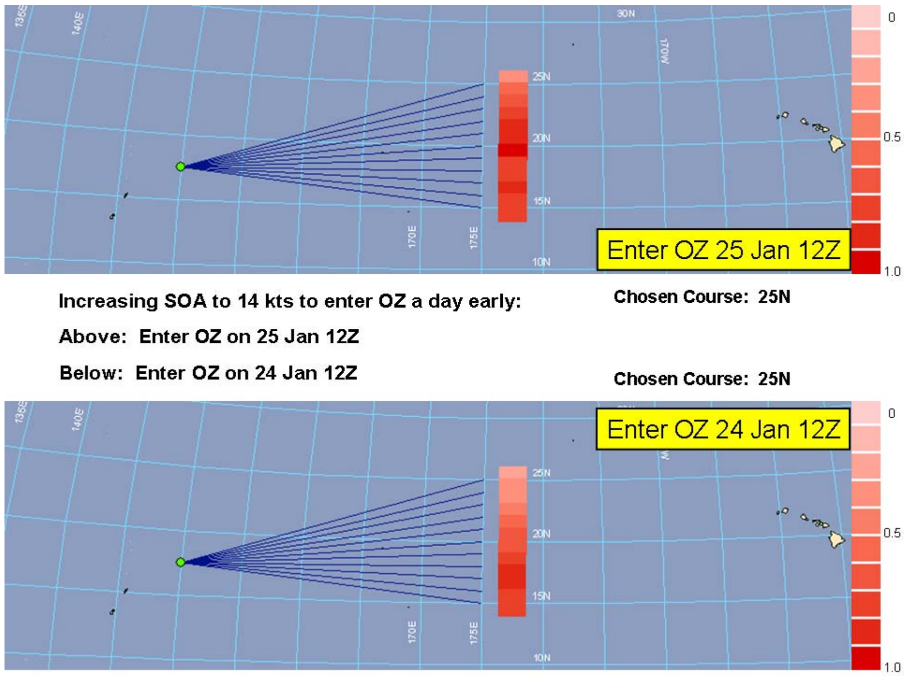


Figure 32. Comparison of early arrival (-4 days) to on-time arrival (-5 days) in OZ.

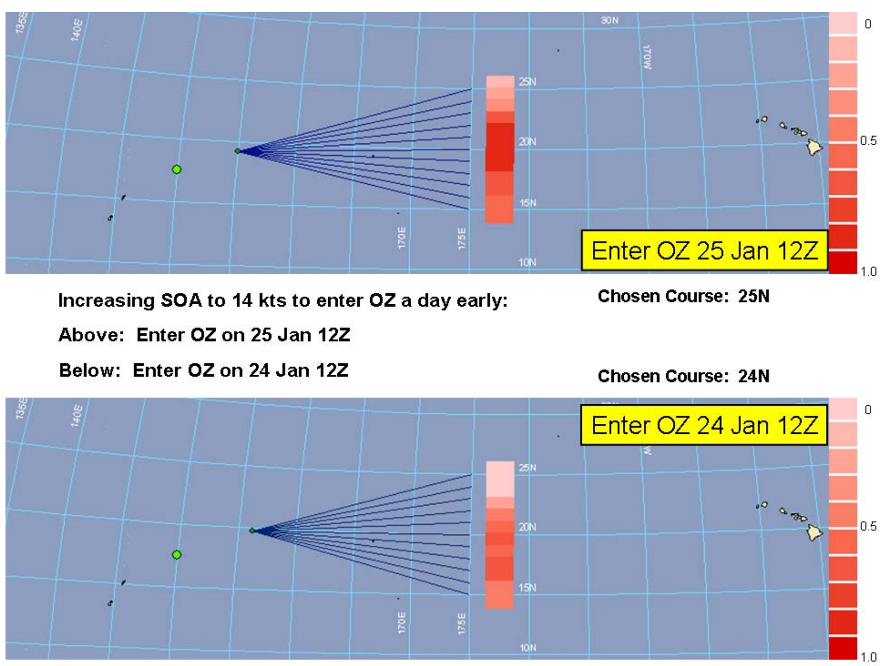


Figure 33. Comparison of early arrival (-3 days) to on-time arrival (-4 days) in OZ.

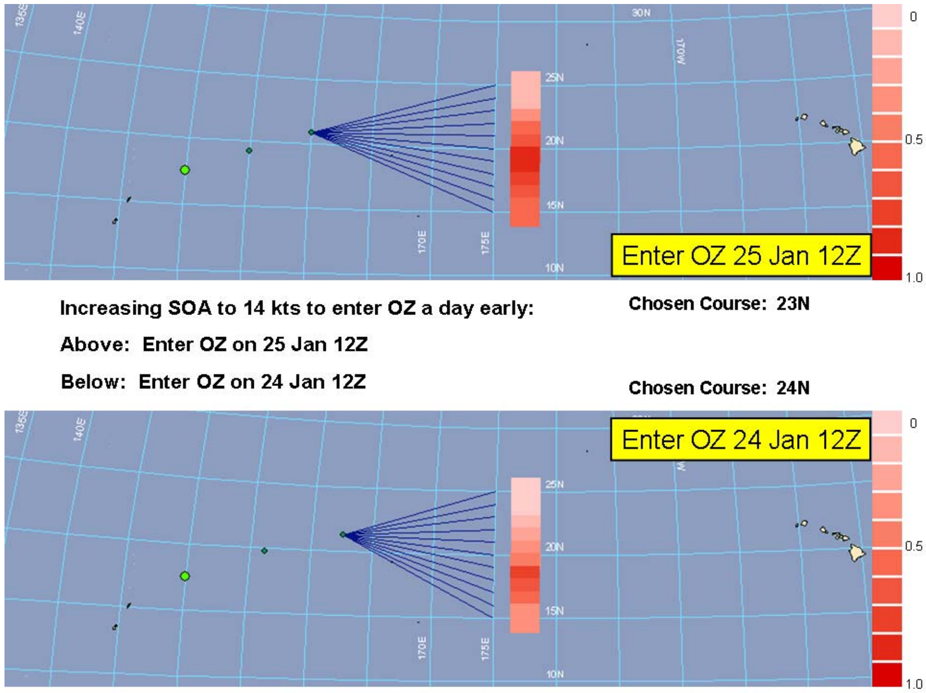


Figure 34. Comparison of early arrival (-2 days) to on-time arrival (-3 days) in OZ.

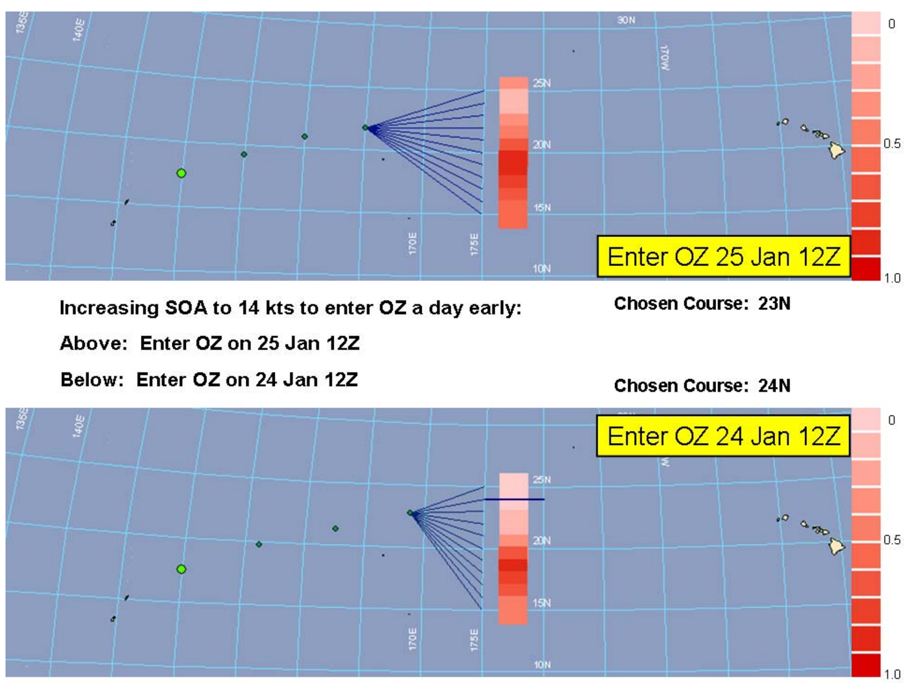


Figure 35. Comparison of early arrival (-1 days) to on-time arrival (-2 days) in OZ.

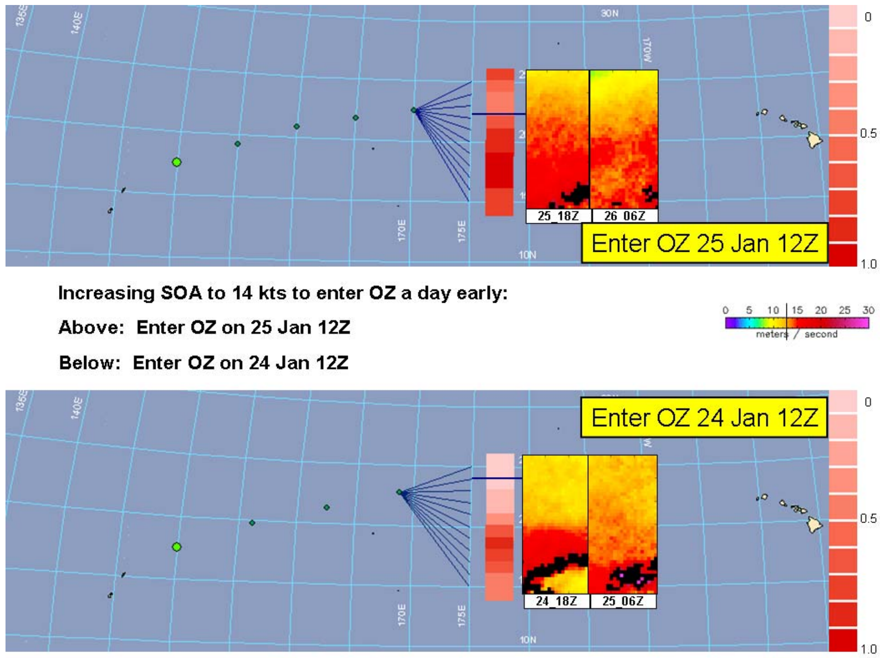


Figure 36. Comparison of early arrival to on-time arrival in OZ, at final decision times, including SSMI (REMSS, 2010).

### 2. November 2009

Figure 37 displays the probability forecasts and expected distances for all the alternatives available to the decision maker at the first decision point. Unlike the January case, the probability of above threshold conditions and the expected distances were forecasted to be equal to or higher at every OZ transit lane for an early arrival except at the southernmost transit lane, 15°N. The optimum direction for on-time arrival was 16°N, while it was 15°N for early arrival.

This situation offered the decision maker a difficult choice from the onset. The optimum decision was to choose the alternative with the lowest expected distance, which was to steam toward 15°N at 14 knots. In making this decision, the decision maker brings in to play the possibility of subsequent elimination of other alternatives. The remaining alternatives for the early arrival were completely dominated by their on-time arrival counterparts at the first decision point.

# Decision time: 29 Oct 12Z
# Forecasts for OZ:

**Enter OZ 03 Nov 12Z**

| Lat Lane | Prob | Expected Distance (km) |
|---|---|---|
| 25N | .82 | 5914 |
| 24N | .92 | 5936 |
| 23N | .96 | 5938 |
| 22N | .94 | 5919 |
| 21N | .90 | 5899 |
| 20N | .76 | 5839 |
| 19N | .72 | 5837 |
| 18N | .70 | 5855 |
| 17N | .50 | 5794 |
| 16N | .36 | 5770 |
| 15N | .28 | 5784 |

**Enter OZ 02 Nov 12Z**

| Lat Lane | Prob | Expected Distance (km) |
|---|---|---|
| 25N | .92 | 5964 |
| 24N | .94 | 5946 |
| 23N | .96 | 5938 |
| 22N | .96 | 5929 |
| 21N | .90 | 5899 |
| 20N | .84 | 5879 |
| 19N | .82 | 5887 |
| 18N | .80 | 5905 |
| 17N | .66 | 5874 |
| 16N | .46 | 5819 |
| 15N | .24 | 5764 |

Figure 37. Probability forecasts and expected distances of OZ transit alternatives for different arrival times—Nov 2009 wind event.

Figures 38–42 compare the baseline scenario with the early arrival scenario at each decision point. In this case, the probabilities for the early arrival were consistently higher, although both arrival days saw their probability forecasts steadily increase as time progressed. The probabilities of above threshold winds on the optimum course at each decision point were 36% (-5 days), 68% (-4 days), 100% (-3 days), 100% (-2 days), and 56% (-1 day) for the on-time scenario. For the early arrival, the probabilities were 24% (-4 days), 48% (-3 days), 42% (-2 days), and 52% (-1 day). The expected distances for the early arrival were also lower at each decision point than those of the on-time case. The early arrival ship consistently steamed toward 15°N throughout its transit.

Figure 42 displays the available SSMI for the times that each ship was in the OZ. Because the observations indicate that the entire OZ was above threshold conditions in both cases, it appears that neither decision scenario would have led to a successful offload.

As with the baseline scenario, the final probability forecast of the early arrival case compares favorably with the observed winds. Both probability forecasts seemed to designate a lower probability of above threshold winds in regions where the SSMI winds were sub-maximum. This is in the northern portion of the OZ for the on-time arrival scenario and in the southern portion of the OZ for the early arrival case. This was an encouraging finding, as the probability forecasts ultimately led each scenario's ship to regions of relatively lower observed wind speeds.

Although both arrival times appear to encounter high winds, a comparison of distance traveled showed that the decision to arrive early produced a better outcome. The distance traveled for the early arrival case was 2681 km, while the on-time vessel would have traveled 2867 km. Though both cases seemed to fail in the objective of completing the offload, the on-time ship went further out of its way and still failed to complete the offload.

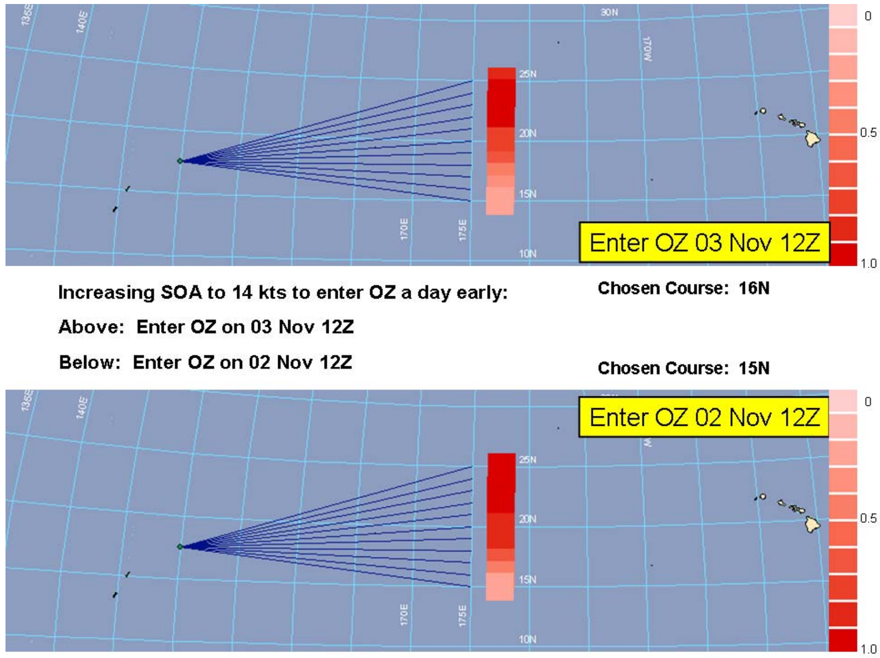


Figure 38. Comparison of early arrival (-4 days) to on-time arrival (-5 days) in OZ.

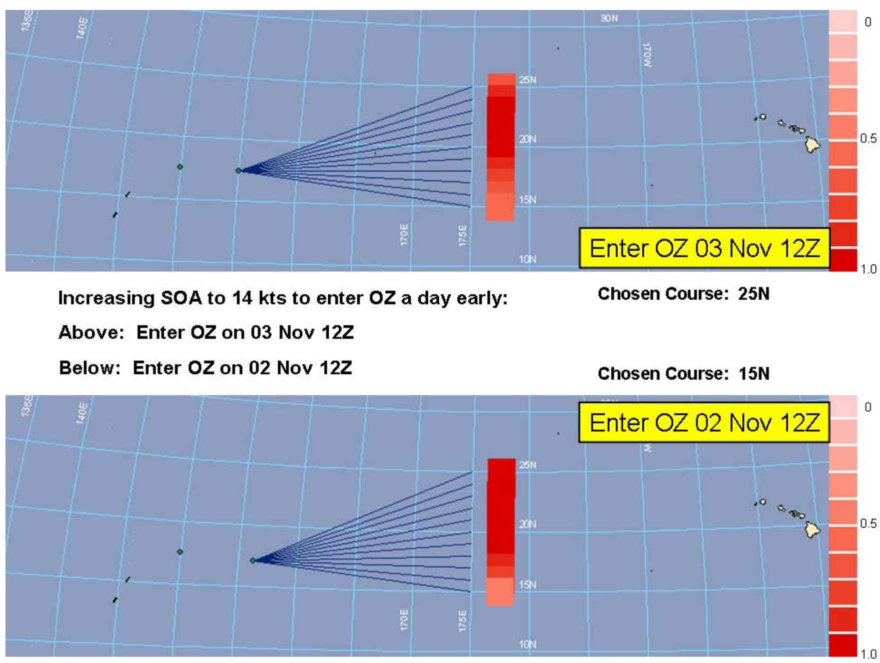


Figure 39. Comparison of early arrival (-3 days) to on-time arrival (-4 days) in OZ.

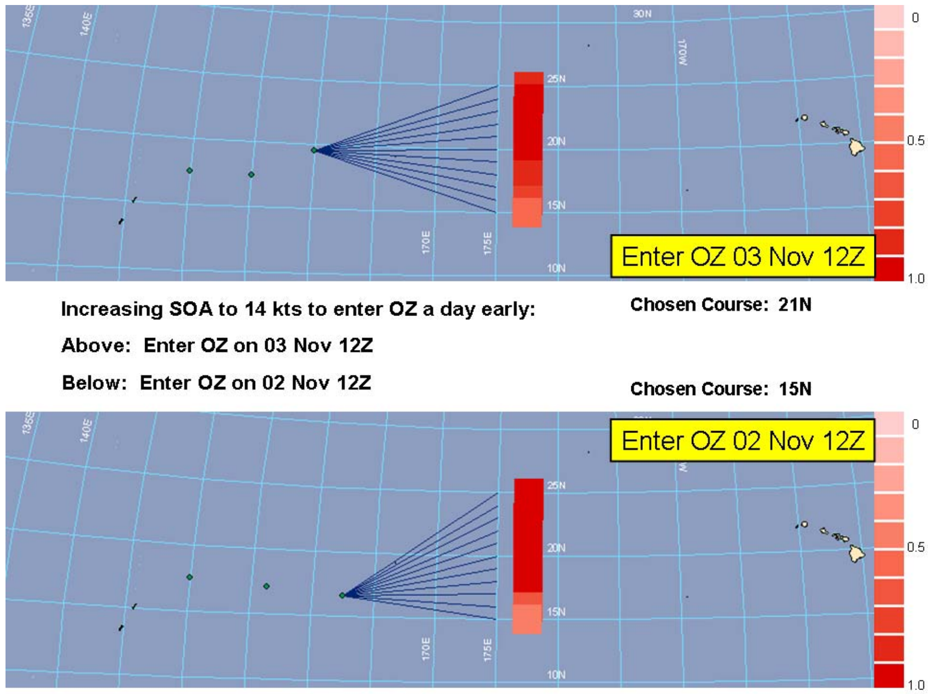


Figure 40. Comparison of early arrival (-2 days) to on-time arrival (-3 days) in OZ.

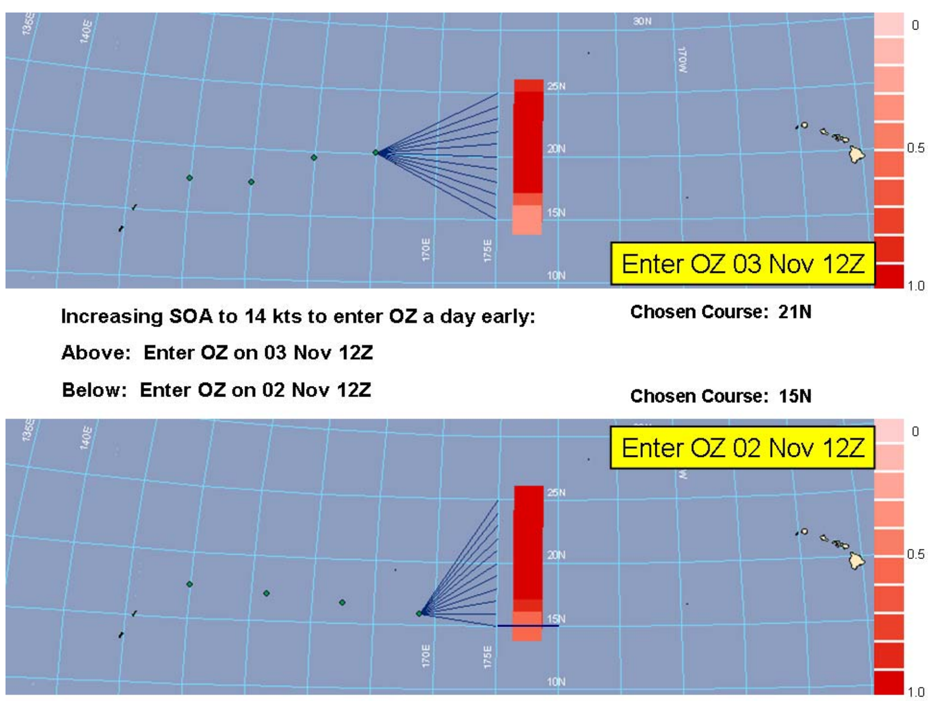


Figure 41. Comparison of early arrival (-1 days) to on-time arrival (-2 days) in OZ.

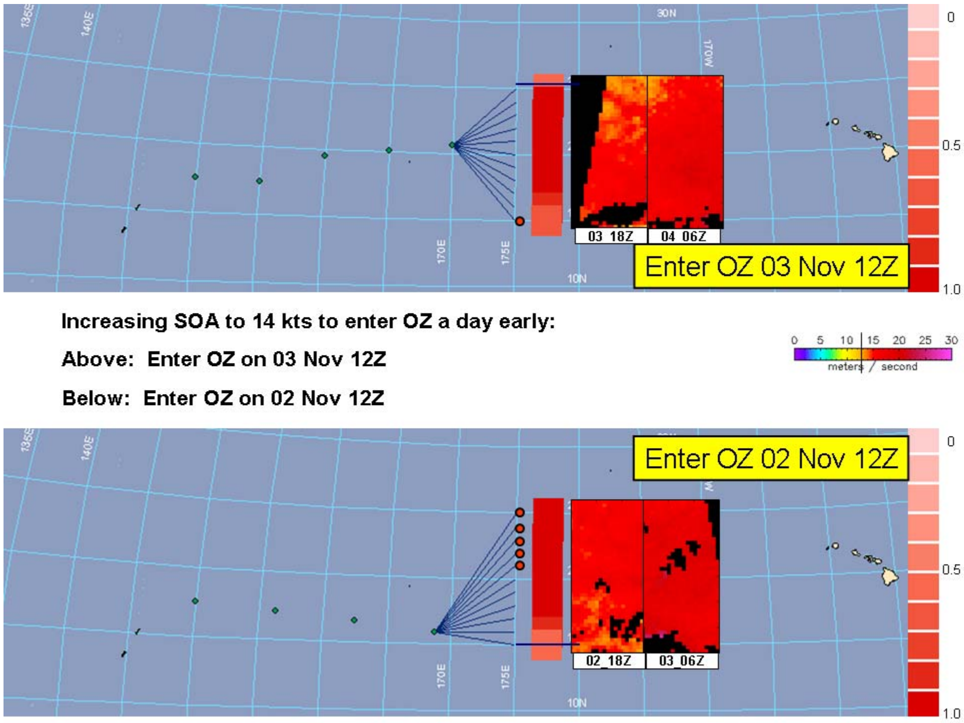


Figure 42. Comparison of early arrival to on-time arrival in OZ, at final decision times, including SSMI (REMSS, 2010).

## E. LONG LEAD TIME FORECAST EXAMPLE

The baseline scenarios for each wind event were extended to include the full extent of the available data, which simulated the inclusion of the probabilistic forecasts earlier in the decision context. The initial decision time was moved two days earlier, or seven days prior to OZ entry. The initial position for the CVN was 16.5°N, 140°E. The ECMWF probability maps allowed for 7.5-day forecasts, but the use of the 12-hour time-late model run in the scenario limited forecasts to seven days.

The 7-day and 6-day forecasts were the only differences in forecasts from the baseline scenario. These forecasts could ultimately also affect the CVN's position at the 5-day decision time.

### 1. January 2009

The first three decision times for the January scenario are shown in Figure 43. At seven days lead time, the forecast probabilities were noticeably lower than the probabilities that were ultimately shown from five days until the final decision point. The 6-day forecast showed increasing probabilities, but the location of the higher probability values near the northern portion of the OZ differed from subsequent forecasts. Because of this variability in the early forecasts, the ship starts toward 23°N, followed by a turn to the south toward 19°N, before turning back to 25°N, as it did at the 5-day point in the baseline scenario.

The result of the early forecasts on the position of the ship at the 5-day decision point was slight. The baseline scenario had the ship starting from 17.5°N, and using the first two available forecasts, the ship was at 18.25°N. Because of this difference in position, the early forecast scenario's actual course to the OZ remains slightly north of the baseline course, even though they chose the same target OZ at each decision point starting at the 5-day point.

Even though both scenarios enter the OZ at 22°N, the early forecast route had a total distance of 2657 km from the 5-day decision point, while the baseline scenario traveled 2681 km over the final five days.

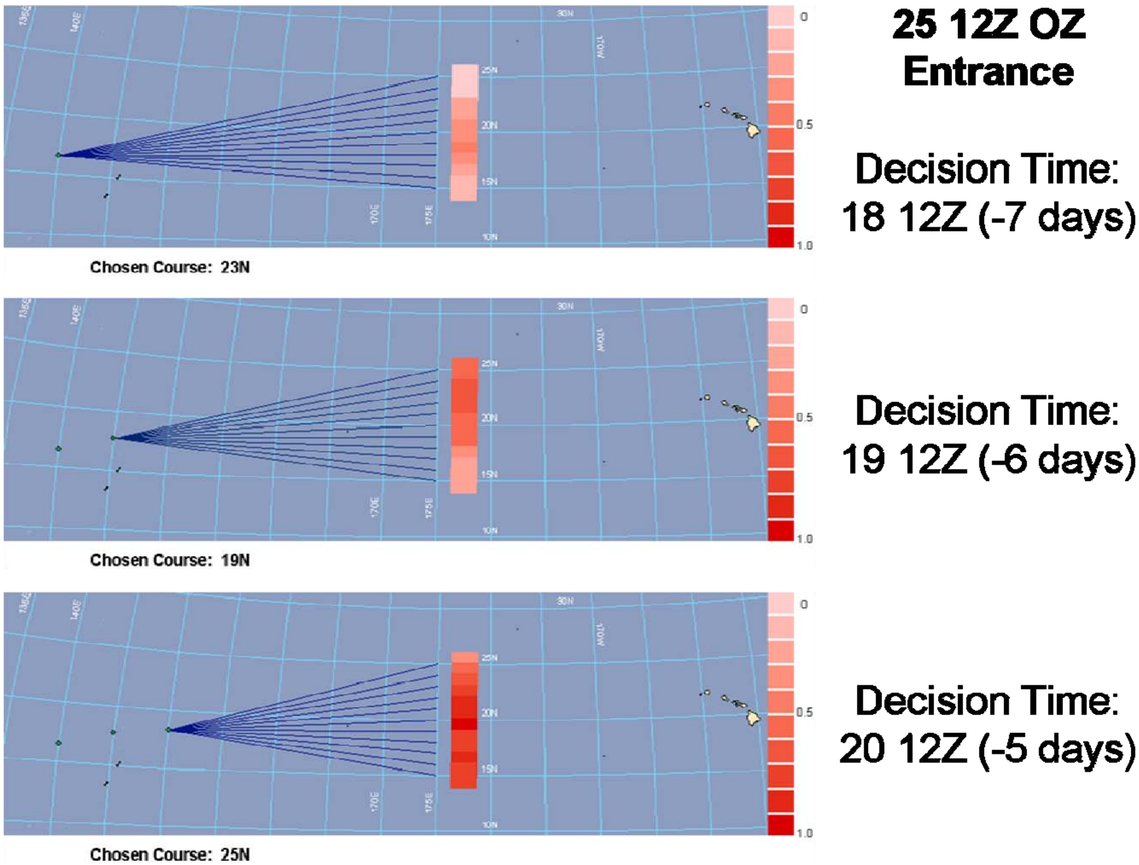


Figure 43. First three decision times of the January 2009 early optimization process.

### 2. November 2009

The first three decision times for the November scenario are shown in Figure 44. At seven and six days lead time, the forecast probabilities were again noticeably lower than the probabilities that were ultimately shown from five days until the final decision point. The distribution of the probabilities, with the higher probabilities in the northern OZ, appeared to be more consistent with the subsequent probability forecasts. The ship started toward 16°N and turned to 18°N the following day before turning back to 16°N at the 5-day decision point. From that point, the early forecast scenario chose the same OZ lanes as the baseline scenario.

The result of the early forecasts on the position of the ship at the 5-day decision point was slight. The baseline scenario had the ship starting from 17.5°N, and using the first two available forecasts, the ship was at 17.2°N. Because of this difference in position, the early forecast scenario's actual course to the OZ remains slightly south of the baseline course, even though they chose the same target OZ at each decision point starting at the 5-day point.

Even though both scenarios enter the OZ at 25°N, the early forecast route had a total distance of 2879 km from the 5-day decision point, while the baseline scenario traveled 2867 km over the final five days.

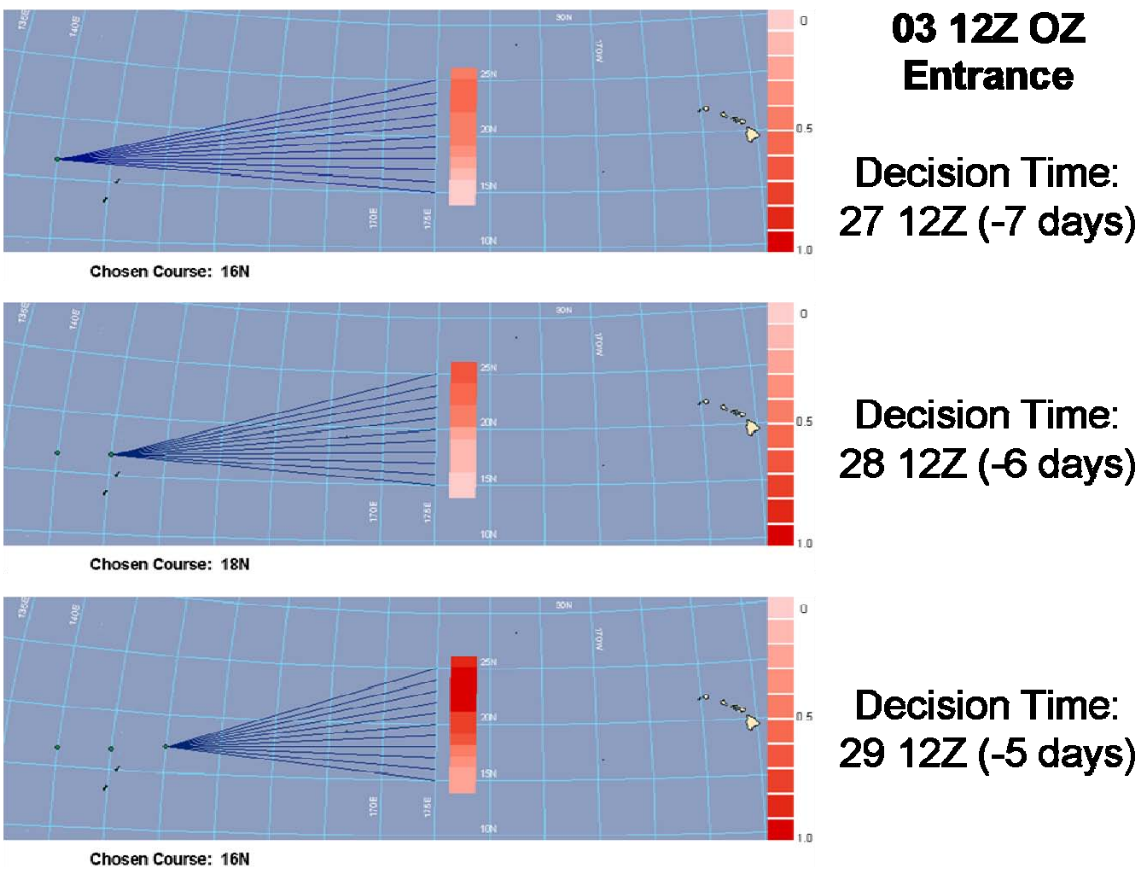


Figure 44. First three decision times of the November 2009 early optimization process.

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# VIII. PROBABILITIES FROM DETERMINISTIC PREDICTION

A sample scenario was run using the control member from the ECMWF ensemble as a deterministic forecast. The decision context was identical to the baseline November scenario, with an OZ arrival of 3 November, 12Z and a consequence penalty of 500 km. The deterministic test was not conducted for the January case.

Using the control forecast at each decision time, a summarized maximum wind speed forecast was produced for each OZ transit lane. The process for creating the summarized maximum winds was the same as for creating the summarized probabilities from the ensemble probability maps. In the deterministic scenario, there was a wind speed map instead of a probability map, and the maximum wind speeds at the entry, middle, and exit regions of the OZ were determined. The maximum of these three values was the summarized maximum wind speed. At each decision time and at each latitude, the summarized maximum wind speeds of the control forecast were forecasted to be greater than the wind speed threshold of 25 knots (12.8 m/s).

In order to put the deterministic forecast into probabilistic terms, a normal distribution was applied to the wind speed threshold of 12.8 m/s, which served as the mean of the distribution. A standard deviation of 1.3 m/s, or 10% of the threshold, was utilized. This simulates a makeshift method of taking forecast uncertainty into account, allowing the estimation of the probability of exceeding the wind speed threshold given a particular wind speed forecast. A comparison of the resultant probabilities from the deterministic control forecast and the probabilities from the ensemble is shown in Figure 45.

Another comparison can be made between the optimum courses determined by the different forecast methods, which are highlighted in Figure 45. For the baseline scenario the following latitude lanes were optimum at each respective decision point from 5 days to 1 day: 16N(5), 25N(4), 21N(3), 21N(3),

25N(1). The deterministic scenario had the following optimum lanes: 23N(5), 25N(4), 25N(3), 25N(2), 25N(1). Both scenarios ultimately enter the OZ at the same latitude, but the ensemble case traveled 2867 km to the OZ, while the deterministic course was 2724 km.

| | Days from Offload Zone | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 5 | | 4 | | 3 | | 2 | | 1 | |
| | Probability | | Probability | | Probability | | Probability | | Probability | |
| Lat Lane | EPS | Det | EPS | Det | EPS | Det | EPS | Det | EPS | Det |
| 25N | 0.82 | 0.84 | 0.68 | 0.59 | 0.86 | 0.65 | 0.86 | 0.53 | 0.56 | 0.56 |
| 24N | 0.92 | 0.78 | 0.82 | 0.78 | 0.94 | 0.76 | 0.98 | 0.82 | 0.94 | 0.73 |
| 23N | 0.96 | 0.80 | 0.94 | 0.82 | 0.98 | 0.92 | 1.00 | 0.93 | 1.00 | 0.89 |
| 22N | 0.94 | 0.90 | 1.00 | 0.90 | 1.00 | 0.95 | 1.00 | 0.97 | 1.00 | 0.95 |
| 21N | 0.90 | 0.95 | 1.00 | 0.97 | 1.00 | 0.98 | 1.00 | 0.99 | 1.00 | 0.97 |
| 20N | 0.76 | 0.99 | 1.00 | 0.97 | 1.00 | 0.99 | 1.00 | 0.99 | 1.00 | 0.98 |
| 19N | 0.72 | 0.95 | 0.96 | 0.97 | 0.96 | 0.98 | 1.00 | 0.98 | 1.00 | 0.98 |
| 18N | 0.70 | 0.95 | 0.88 | 0.89 | 0.88 | 0.84 | 1.00 | 0.88 | 1.00 | 0.97 |
| 17N | 0.50 | 0.86 | 0.78 | 0.88 | 0.86 | 0.82 | 0.96 | 0.88 | 1.00 | 0.94 |
| 16N | 0.36 | 0.84 | 0.64 | 0.88 | 0.74 | 0.86 | 0.68 | 0.99 | 0.88 | 0.68 |
| 15N | 0.28 | 0.89 | 0.54 | 0.68 | 0.52 | 0.70 | 0.40 | 0.73 | 0.64 | 0.53 |

Figure 45. Comparison of probabilities derived from the ECMWF EPS (black) and the ECMWF control forecast (red) for 3 November 2009 OZ entry. Optimum OZ lane at each decision point highlighted.

# IX. SUMMARY AND CONCLUSIONS

## A. SUMMARY

Motivated by the Battlespace on Demand Concept of Operations, we selected a decision problem and set out to address the “what if”—what if we applied the forecast and statistical tools available today to try to optimize a real world decision?

The decision context for a CVN ammunition cross-deck evolution was modeled using multiple decision points. We used distance as the measure of utility of the decision consequences, and wind speed of 25 knots as the threshold for conditions preventing a successful evolution.

Monthly mean winds were shown to have limited usefulness in long-range planning. If monthly mean winds were used to determine the most desirable month or season to conduct an offload, tropical cyclone season would be favored. Monthly means were not particularly beneficial in terms of optimization.

Monthly frequency of occurrence plots provided quantitative information that allowed for the determination of optimum tracks in long-range planning. Sustained wind surges in the easterly trades in excess of 25 knots in the region are rare, at less than 5% probability across all months. The great circle route is the optimum course due to the infrequency of the wind surges.

Identification of historical high trade wind events was a laborious endeavor, and events related to tropical cyclones complicated the process. We selected three cases having durations longer than one day for further analysis, with two of those being used as test cases for decision analysis. Analysis of these identified cases showed that all were associated with anomalously strong surface high pressure in the Northern Pacific. Therefore, it is likely that forecasts of the strength of the North Pacific anticyclone could be useful as an indication to consider a decision model for transit through the OZ.

Probability forecasts derived from the ECMWF ensemble prediction system indicated the possibility of easterly trades greater than 25 knots in the OZ at lead times of 5–7 days. Ensemble reliability for this parameter, threshold, and location is unknown.

Selecting optimum tracks at 24-hour intervals resulted in time sequences that, in general, had the example ships making small course changes to the north or south. Successive, extreme changes of direction were infrequent.

The minimum probability of above threshold winds and the minimum expected distance were almost always collocated along the same latitude alternative in the January case. They were only collocated approximately half the time in the November case.

Raising the consequence penalty affected the decisions, especially in the November case. The scenarios with higher consequences yielded more conservative decisions. The optimization process did not appear to completely avoid 25 knot winds, even in cases with higher consequence penalties.

A decision alternative of speeding up to enter the OZ earlier than planned was introduced. In the January case, this alternative appeared to position the ship in below threshold conditions within the OZ. It was unable to do so in the November case, as the entire OZ seemed to be above threshold.

There was a noticeable increase in the ensemble uncertainty forecasts from the early lead times of 6–7 days to the later lead times. Inclusion of 7- and 6-day forecasts did not change the final OZ transit lane determined by starting with 5-day forecasts. The early forecasts shortened the total distance traveled for the January case and lengthened it for the November case.

Finally, we tested the same decision scenario as if no ensemble-based probabilities were available by using a single deterministic forecast and making the crude assumption of Gaussian error in the wind speed forecast. Probabilities

were fairly similar to those produced by the ensemble, but the location of the minimum probability OZ was more consistent from day 5 to day 1, which resulted in a more efficient track.

## B. CONCLUSIONS

Although monthly mean winds provide information about the best and worst locations and times of year to conduct offload evolutions, this is not particularly useful as CSG deployments and operations are not scheduled around weather events, at least in the long-range planning phase. Frequency of occurrence information for a specific parameter, threshold, and location, was more useful than monthly means when optimizing of this decision.

The ability to select the specific operational wind threshold that limited the offload was critical to analysis of the decision problem. Off the shelf ensemble products, such as those from the Navy's global model, NOGAPS, produce similar probabilistic forecasts, e.g., gale probability forecasts. However, the presence of multiple threshold levels or the ability to select a specific threshold would be even more helpful in optimization efforts.

Accessible reliability statistics seemed to be lacking for many global NWP ensembles. This statistical information is a vital consideration in the optimization of decisions and is a major component of accurate characterization of uncertainty.

Using a single deterministic forecast but taking uncertainty into account can provide an intuitive means of estimating probabilities in the absence of an ensemble. However, the forecast error standard deviation should be determined by performance statistics rather than our ad hoc method.

Throughout the study, decision outcomes were affected by both the makeup of the decision context itself and by the probabilistic forecast inputs.

## C. RECOMMENDATIONS

Further work in applying statistical forecast information to optimize everyday military operational decisions is needed. First, a catalogue or list of common or recurring decision types should be maintained so that the decisions themselves can be studied with greater rigor. Improving the realism of the basic decision context to include a more comprehensive suite of decision alternatives and a more complete measure of the decision makers' utility function would improve the usefulness of the studies. It may be that an optimization strategy that considers future possible decisions in the present decision would yield more realistic outcomes.

Additionally, further refinement of the method for determining forecast probabilities would likely improve the results. The democratic voting method is not the best scheme for determining forecast probabilities, especially in ensembles with fewer members than the one used in this study.

Both ensemble and deterministic model verification statistics should be collected and made easily accessible. These statistics could be used for calibration purposes, and to increase confidence in the uncertainty information.

Similar analyses using forecasts from other ensemble prediction systems such as the North American Ensemble Forecast System and NOGAPS Ensemble would also help develop ways of implementing decision support under BOND.

Finally, other decision contexts should be examined. Analysis of decisions that have different time and spatial scales, different or multiple parameters, higher or lower thresholds, and diverse locations is needed. Deeper knowledge of the both the decision contexts and the environmental constraints that affect them will improve the way our knowledge of meteorology and oceanography is applied to military operations.

# APPENDIX A: CLIMATOLOGY

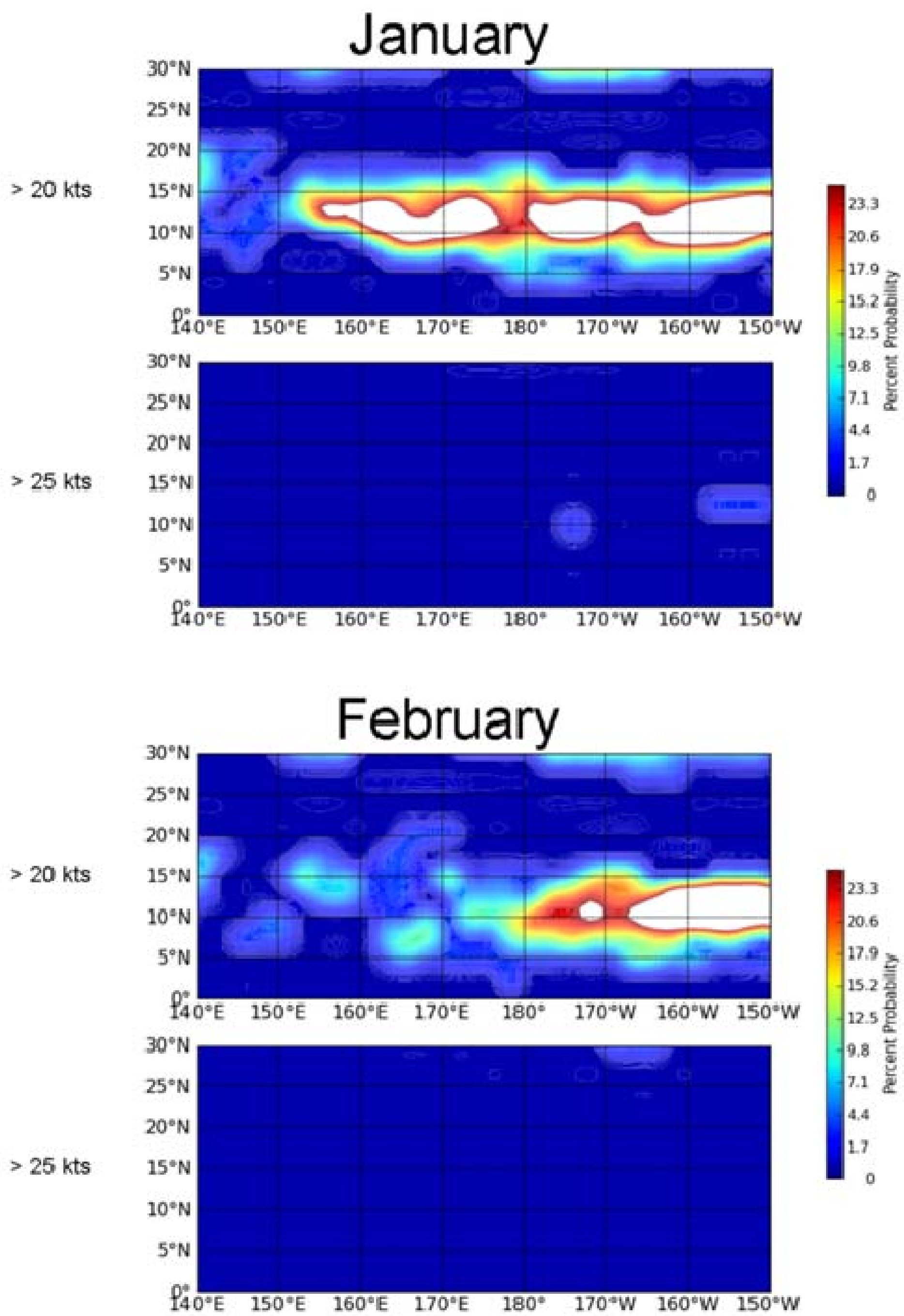



Figure 46. Historical frequency of exceeding 20 knot (top) and 25 knot (bottom) winds, Jan-Feb (ACAF, 2010).

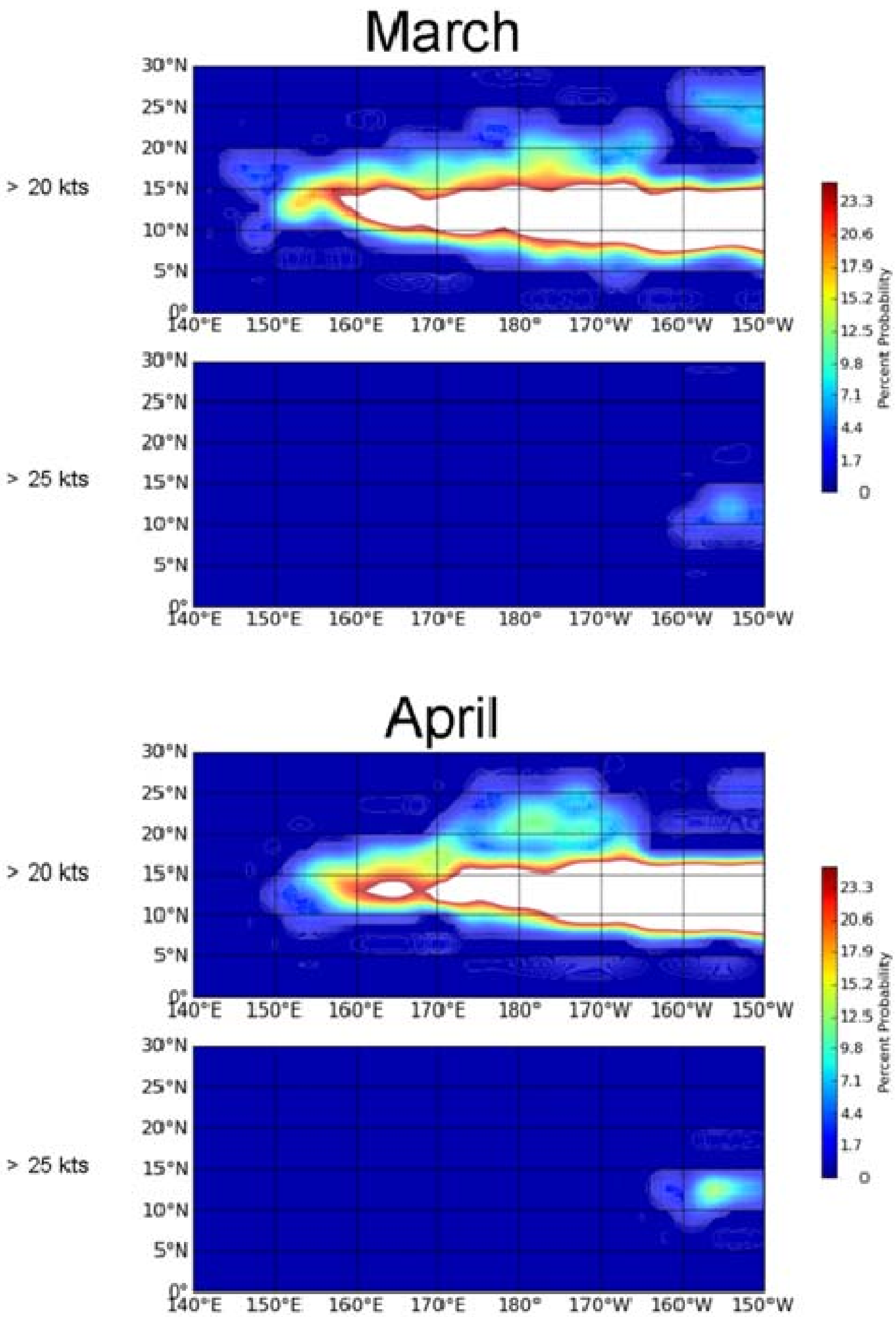



Figure 47. Historical frequency of exceeding 20 knot (top) and 25 knot (bottom) winds, Mar-Apr (ACAF, 2010).

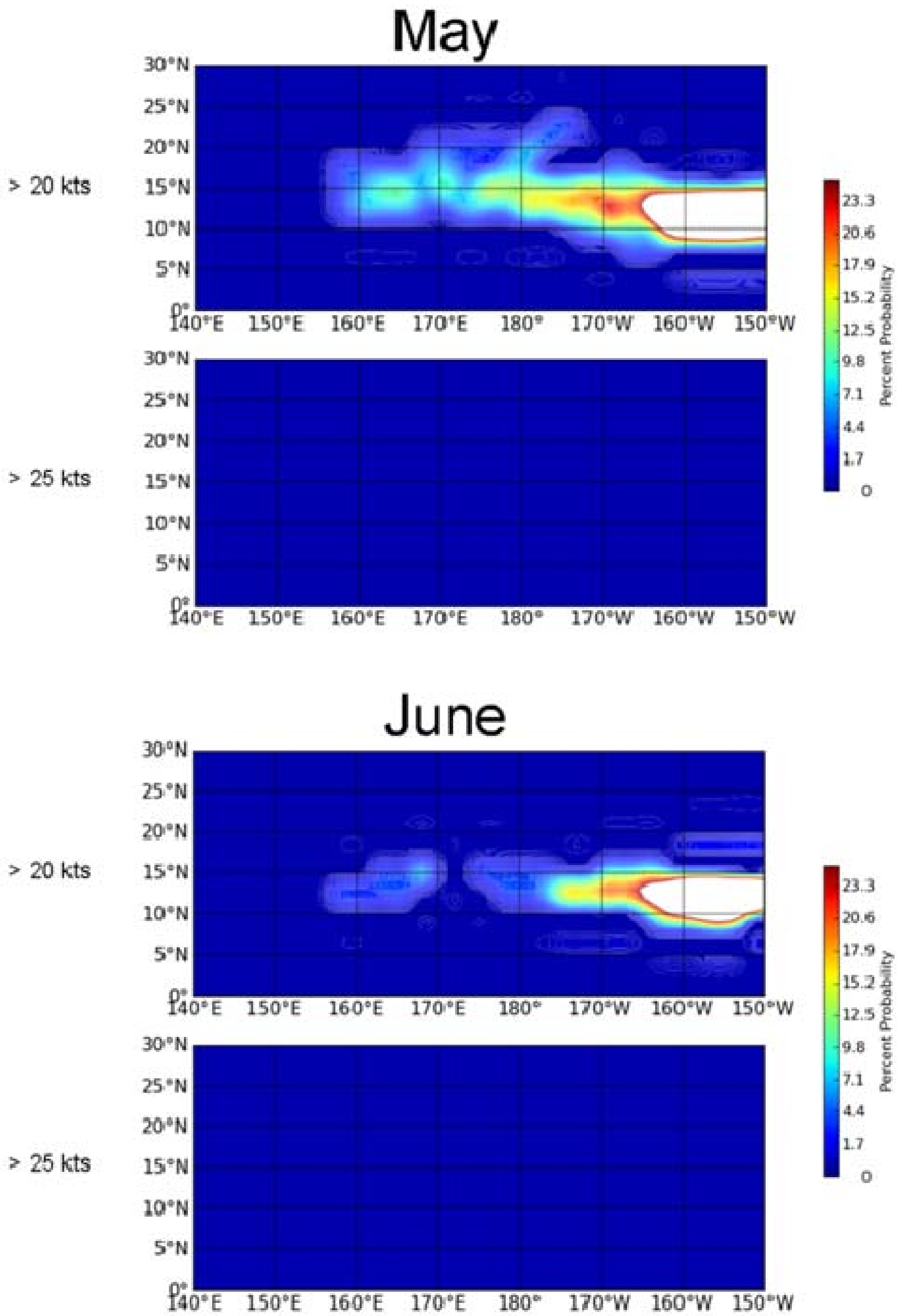



Figure 48. Historical frequency of exceeding 20 knot (top) and 25 knot (bottom) winds, May-Jun (ACAF, 2010).

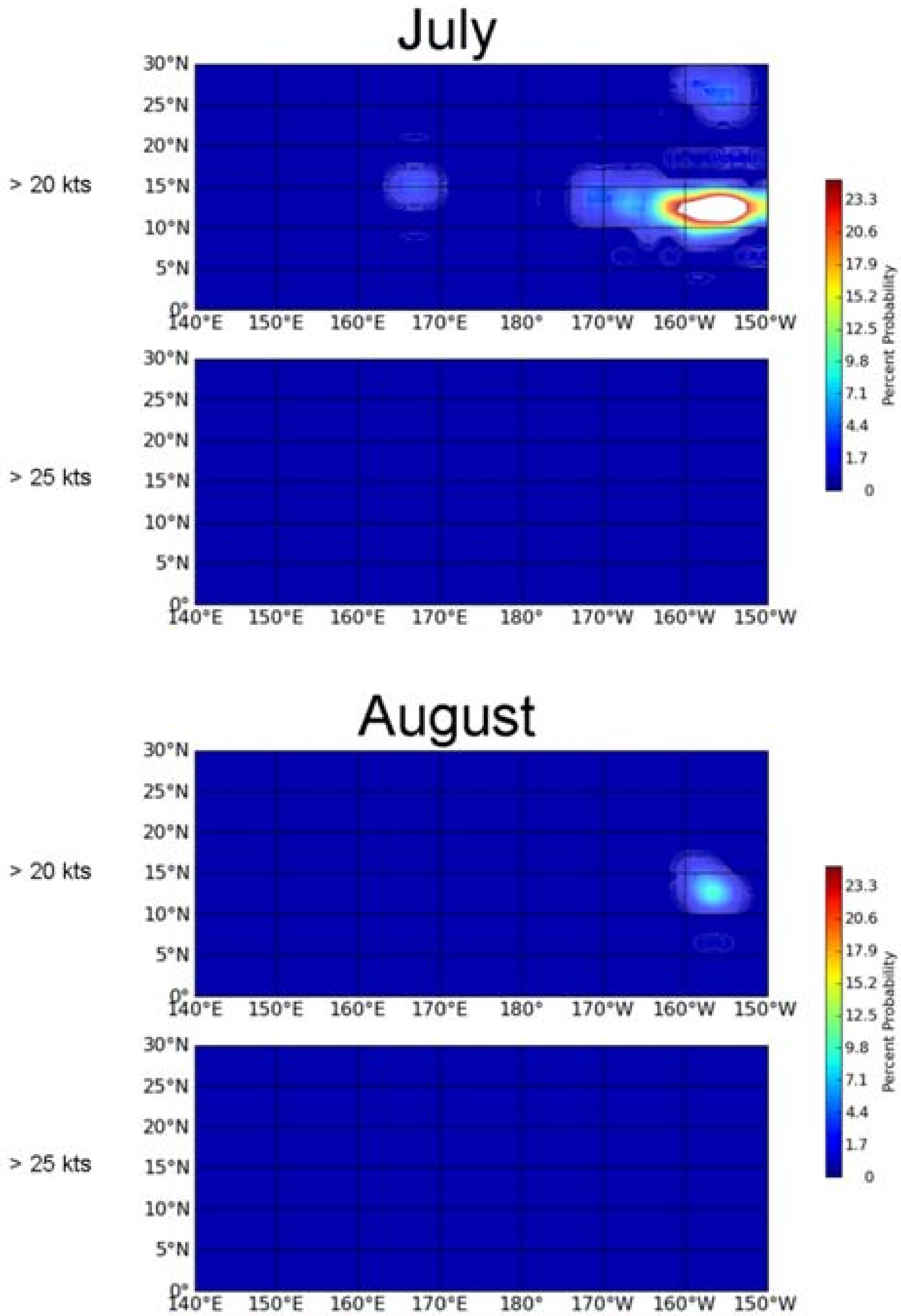



Figure 49. Historical frequency of exceeding 20 knot (top) and 25 knot (bottom) winds, Jul-Aug (ACAF, 2010).

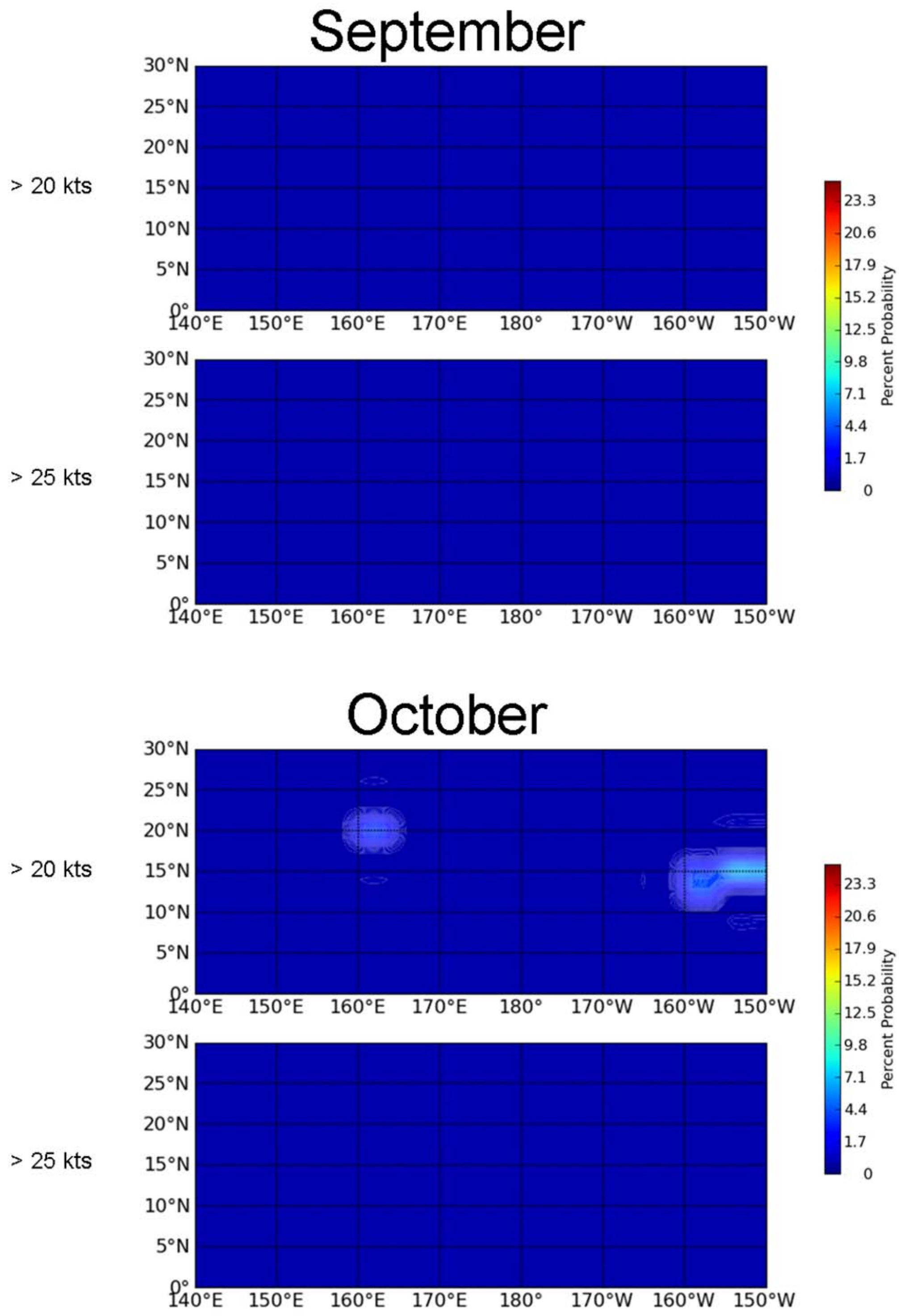



Figure 50. Historical frequency of exceeding 20 knot (top) and 25 knot (bottom) winds, Sep-Oct (ACAF, 2010).

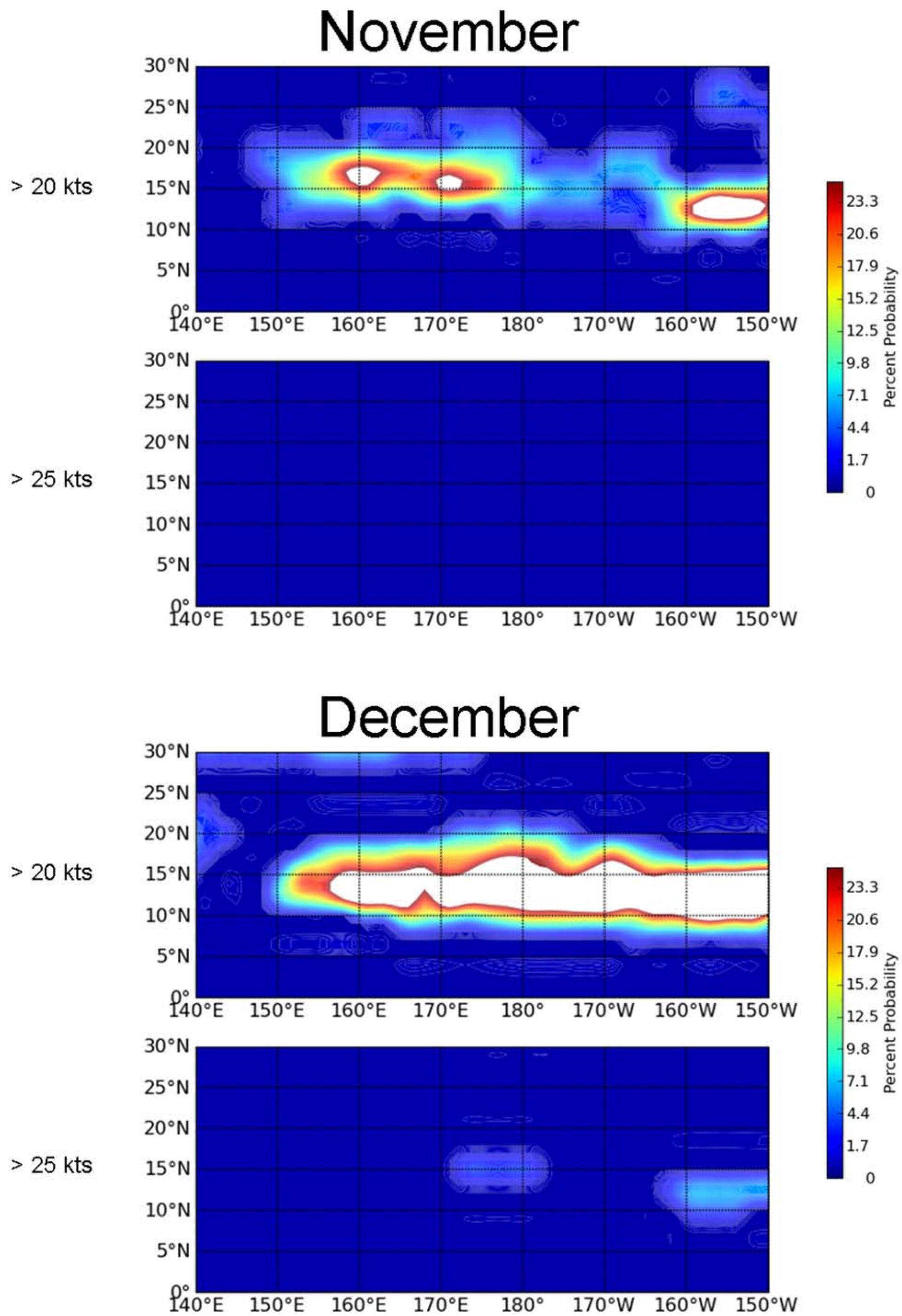



Figure 51. Historical frequency of exceeding 20 knot (top) and 25 knot (bottom) winds, Nov-Dec (ACAF, 2010).

# APPENDIX B: WIND EVENT CASES

## A. APRIL 2008

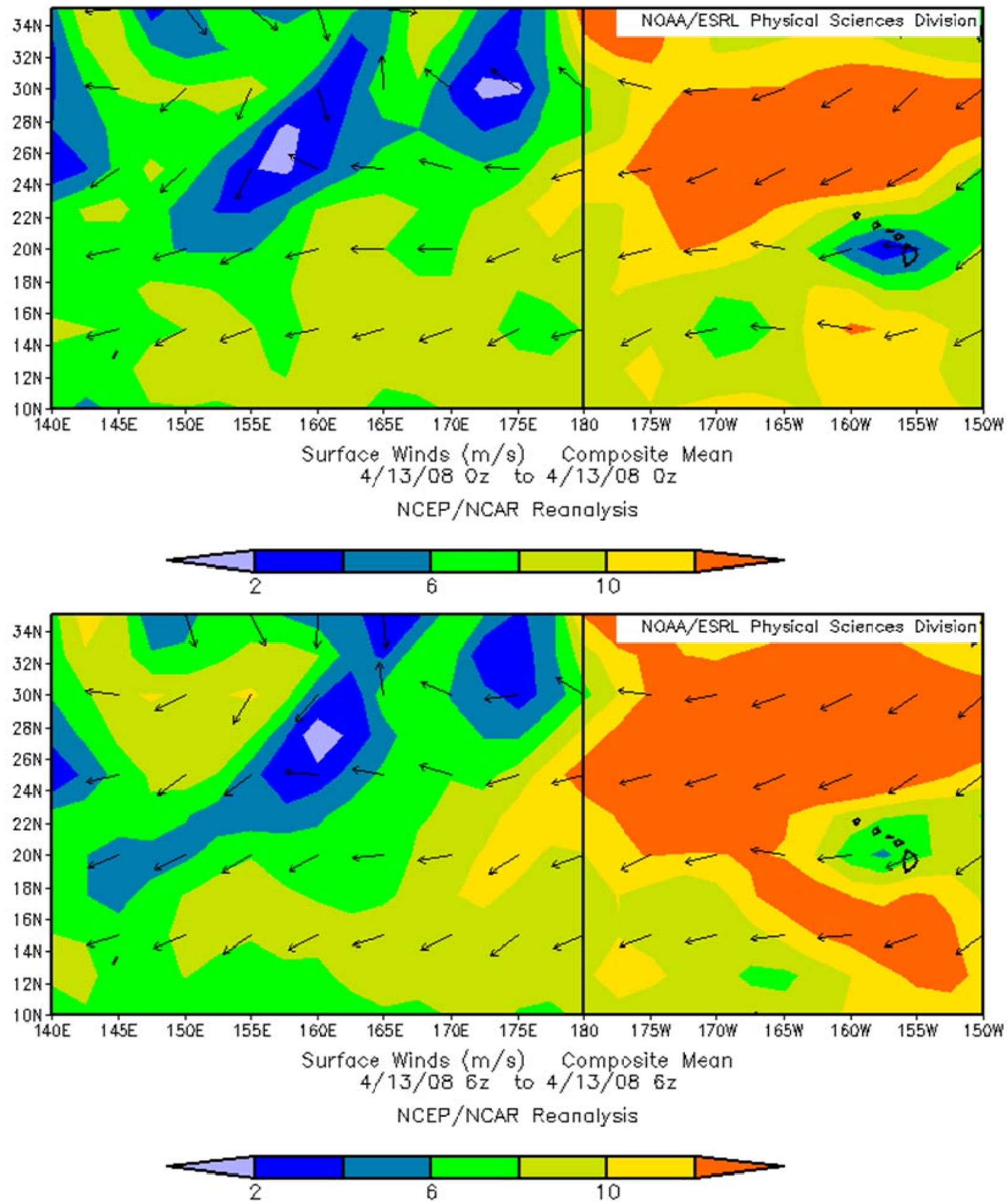



Figure 52. April 2008 wind event; 13 April 00Z, 06Z (ESRL, 2010).

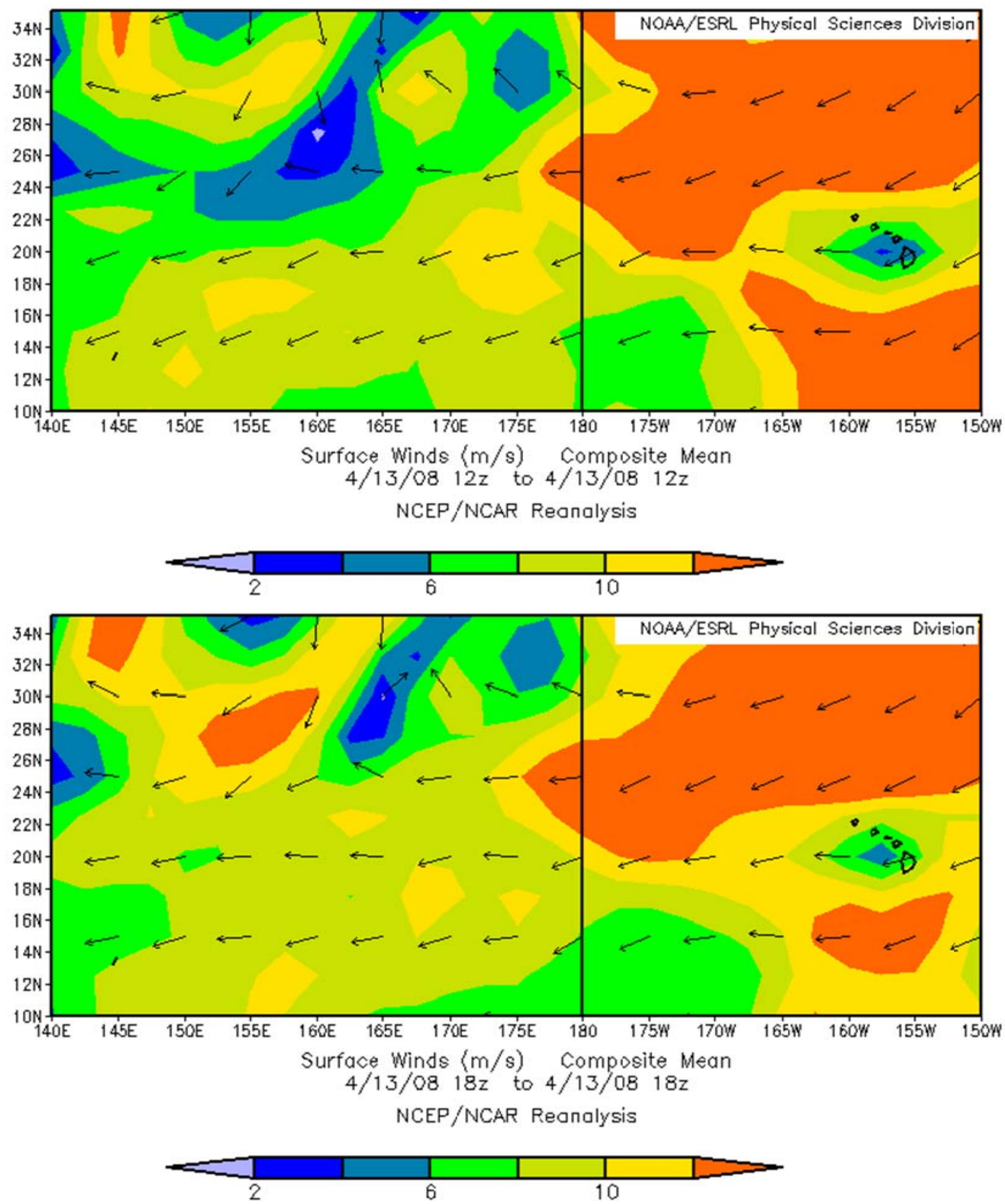



Figure 53. April 2008 wind event; 13 April 12Z, 18Z (ESRL, 2010).

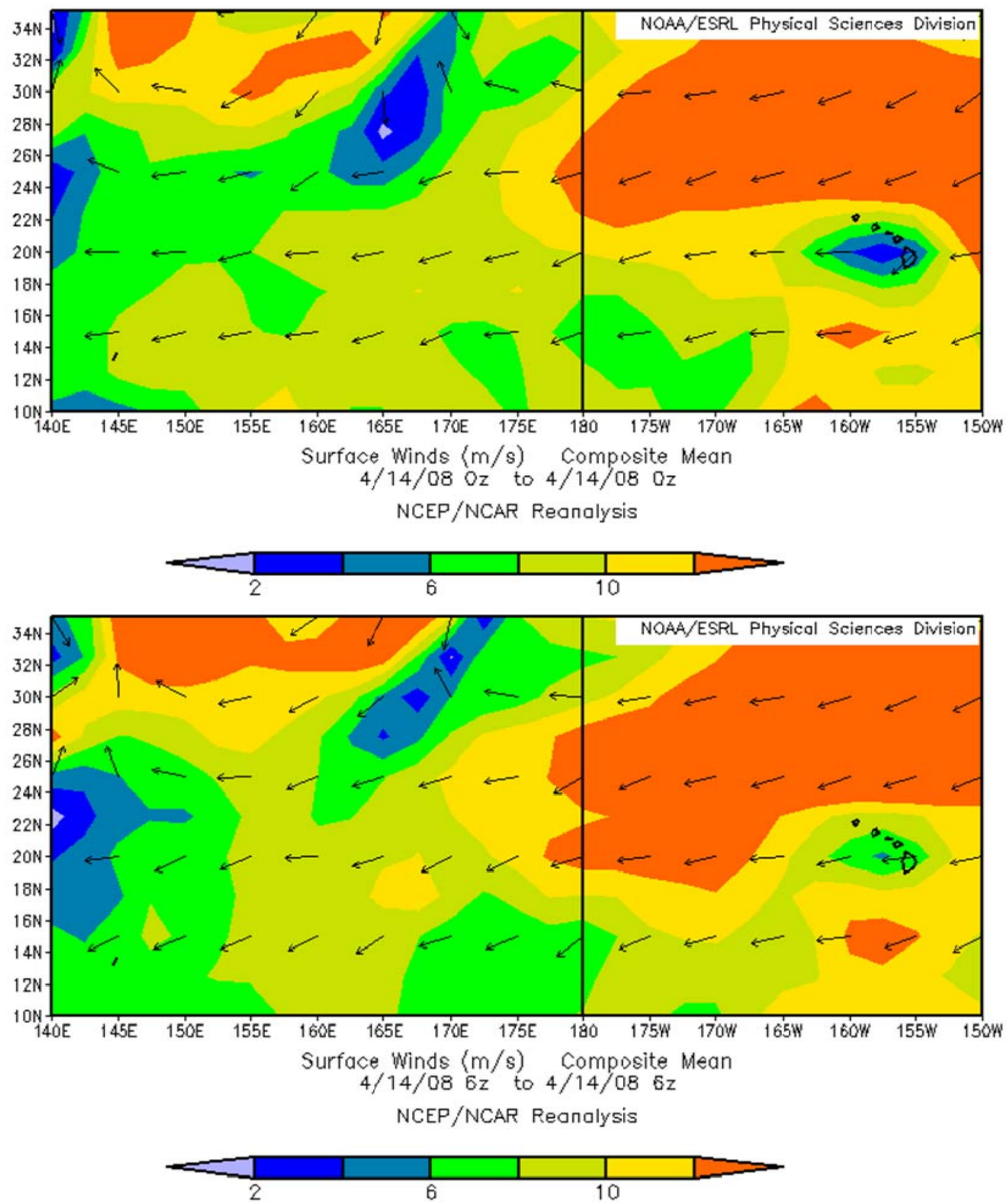



Figure 54. April 2008 wind event; 14 April 00Z, 06Z (ESRL, 2010).

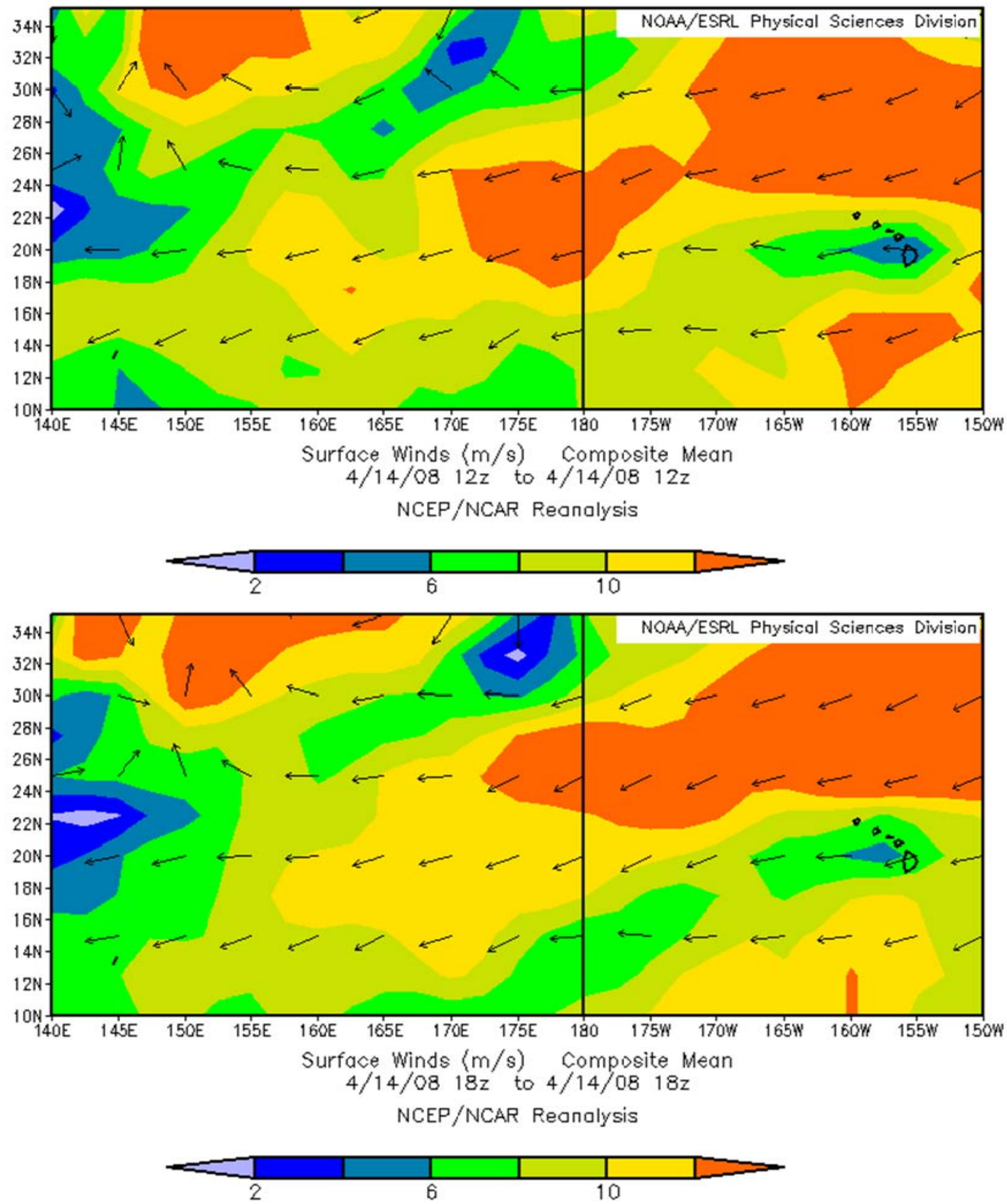



Figure 55. April 2008 wind event; 14 April 12Z, 18Z (ESRL, 2010).

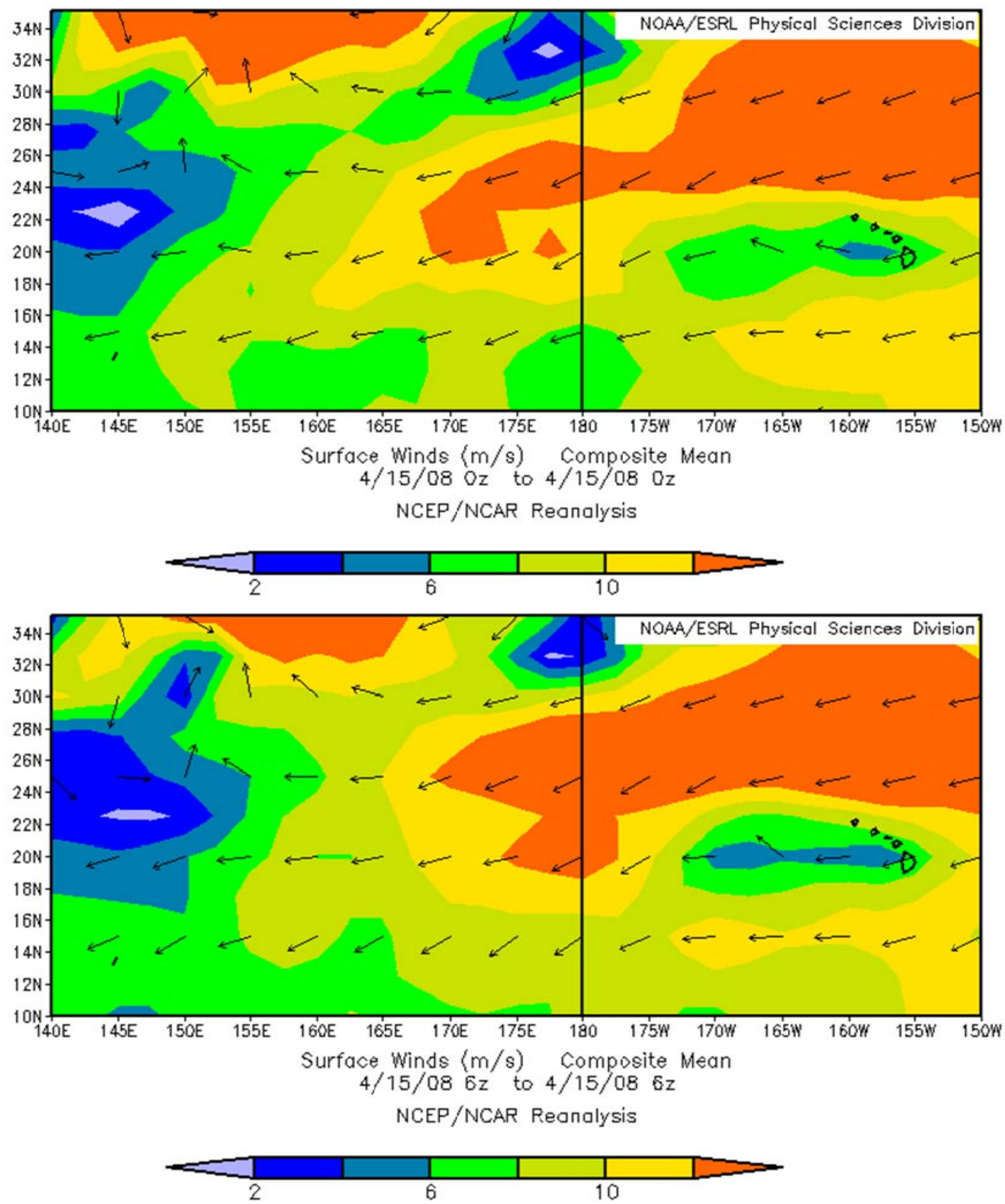



Figure 56. April 2008 wind event; 15 April 00Z, 06Z (ESRL, 2010).

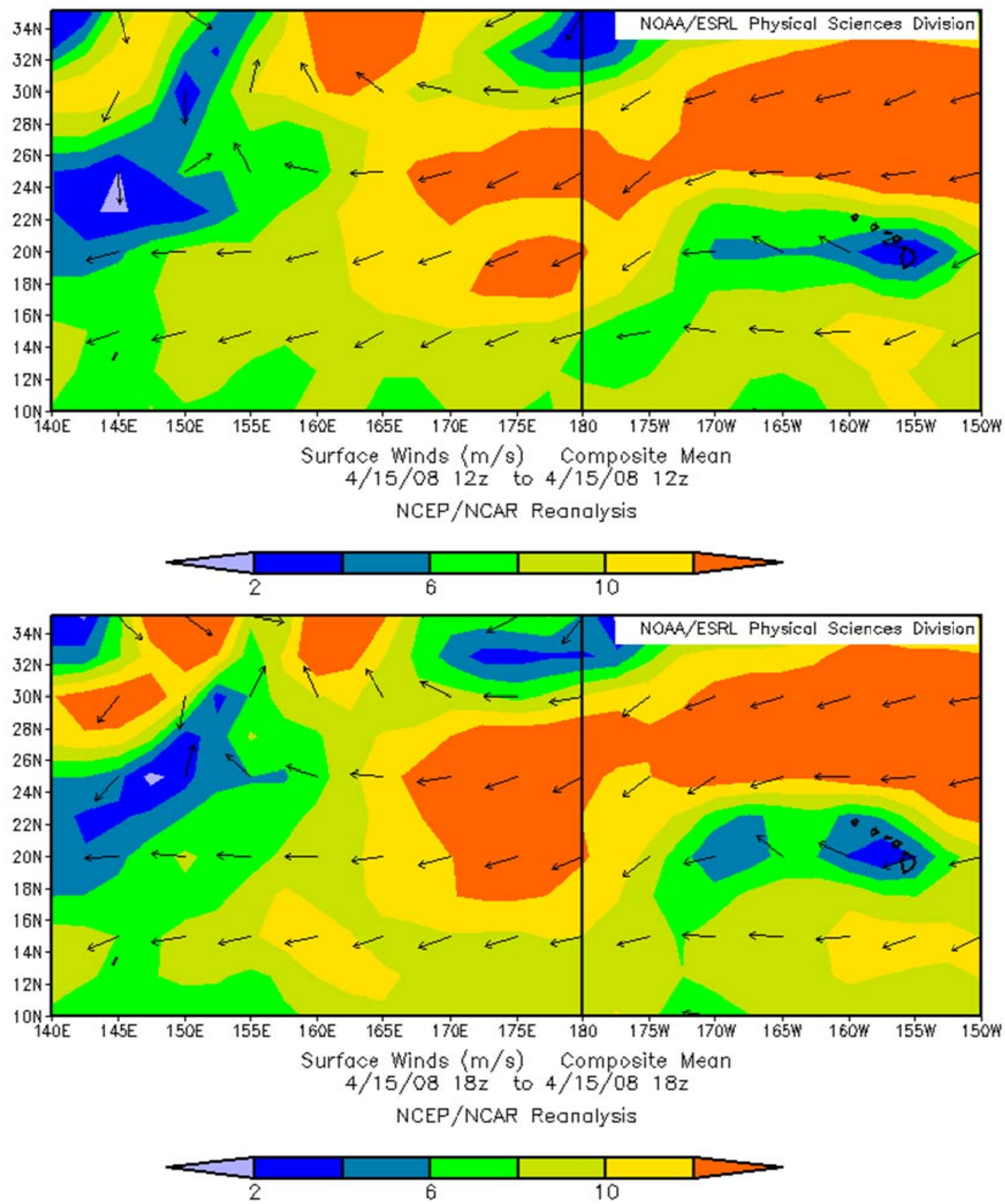



Figure 57. April 2008 wind event; 15 April 12Z, 18Z (ESRL, 2010).

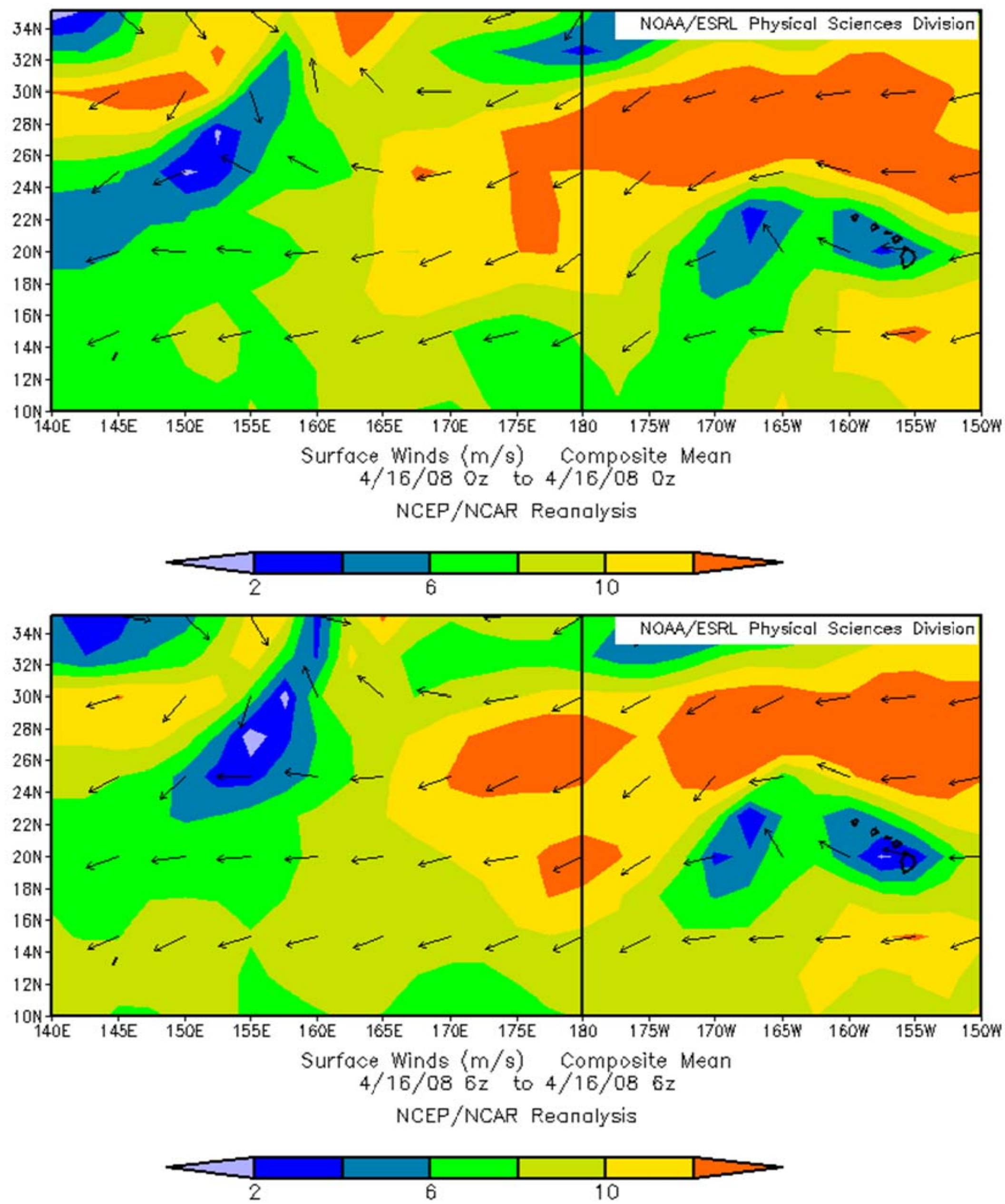



Figure 58. April 2008 wind event; 16 April 00Z, 06Z (ESRL, 2010).

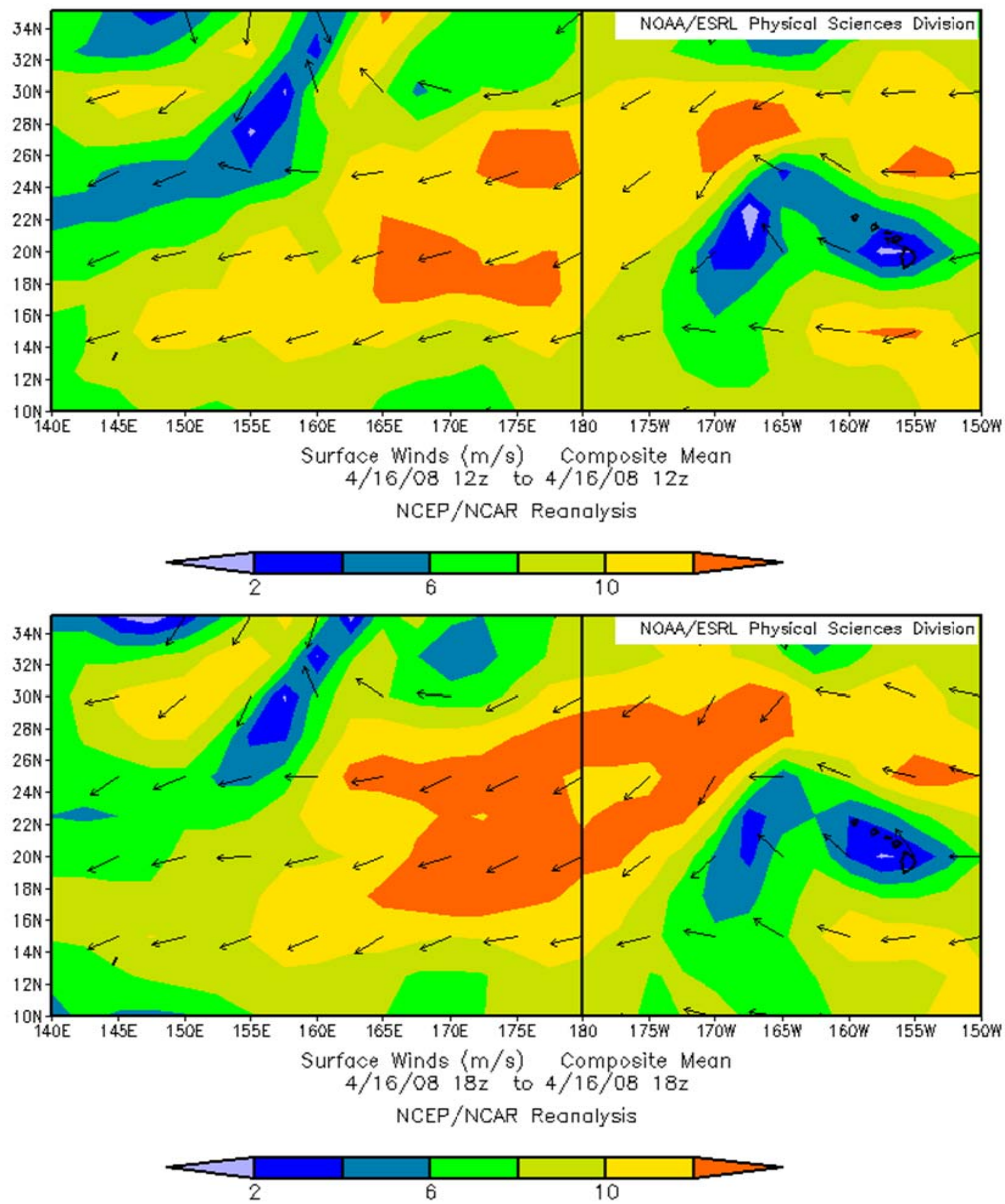



Figure 59. April 2008 wind event; 16 April 12Z, 18Z (ESRL, 2010).

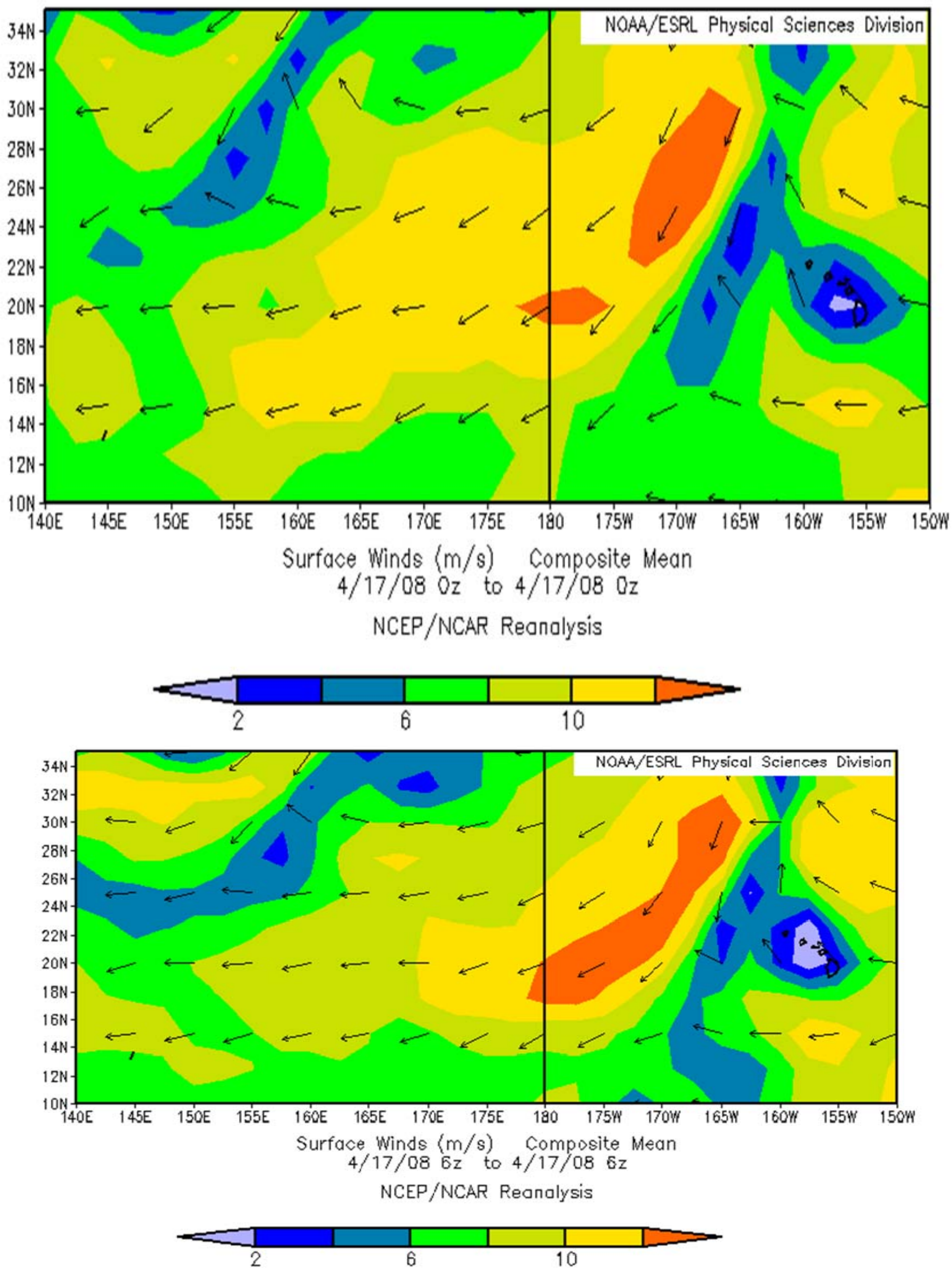



Figure 60. April 2008 wind event; 17 April 00Z, 06Z (ESRL, 2010).

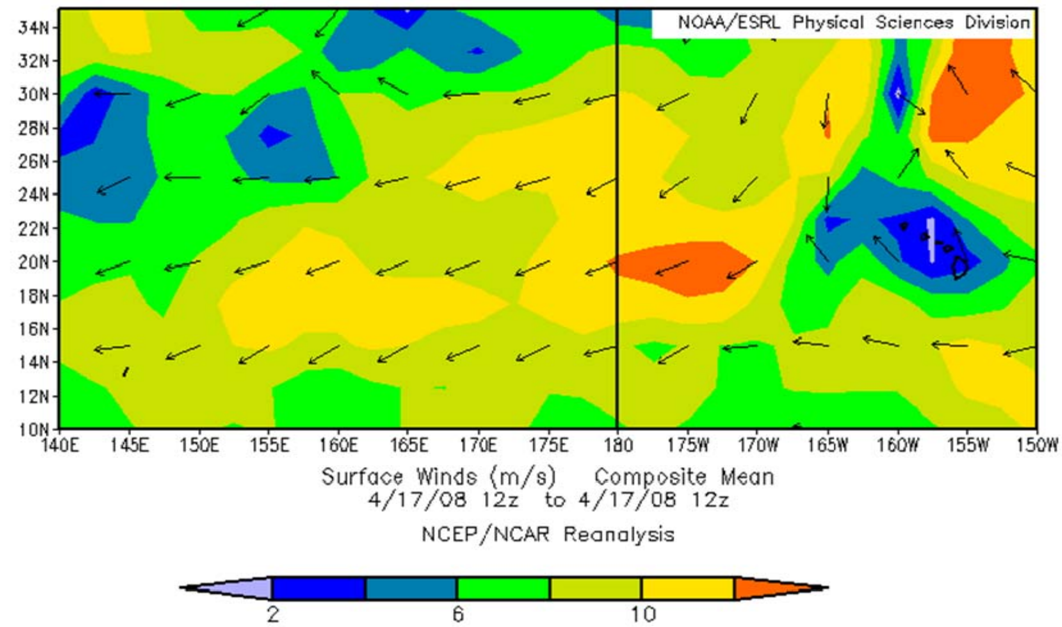



Figure 61. April 2008 wind event; 17 April 12Z (ESRL, 2010).

## B. JANUARY 2009

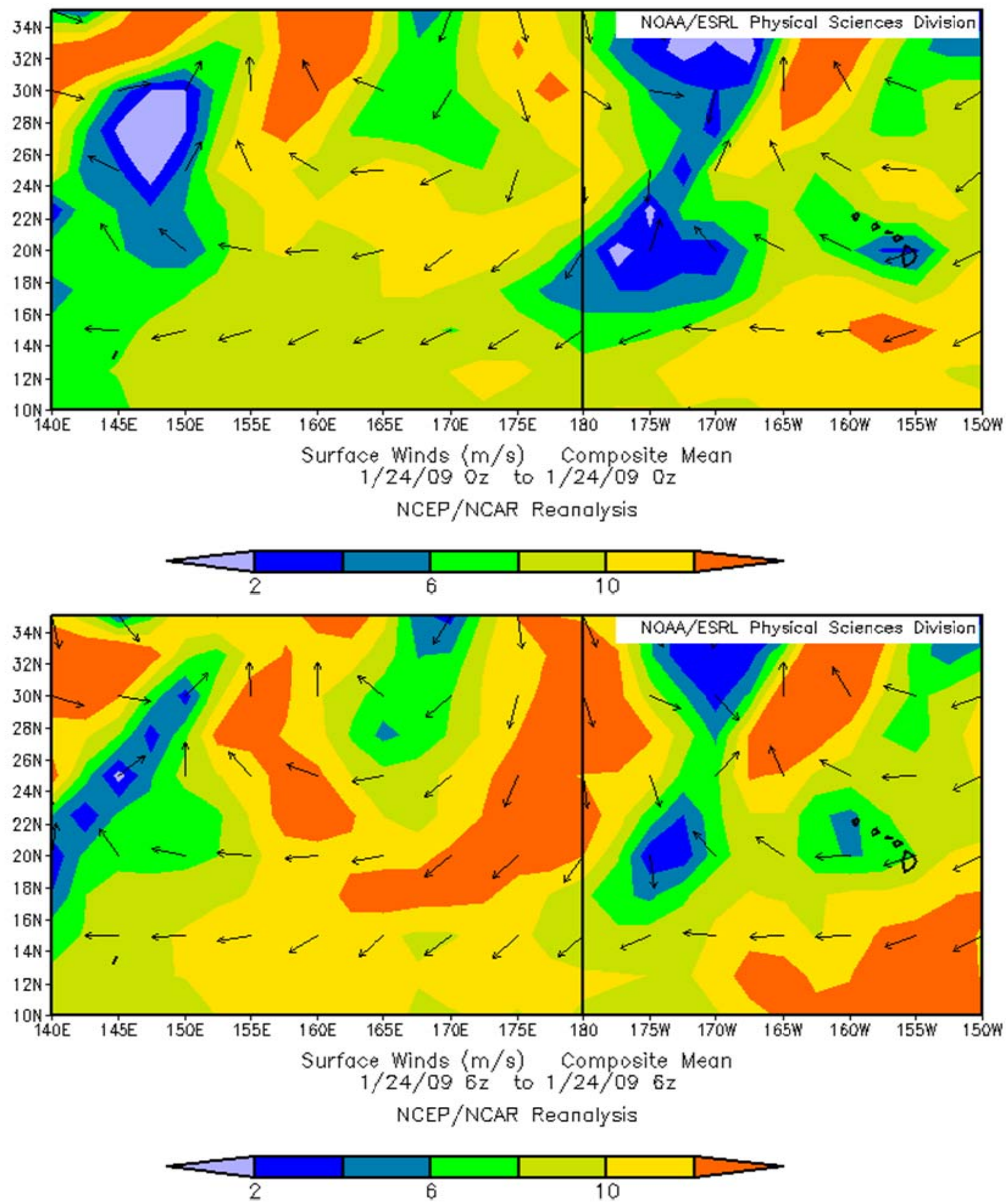
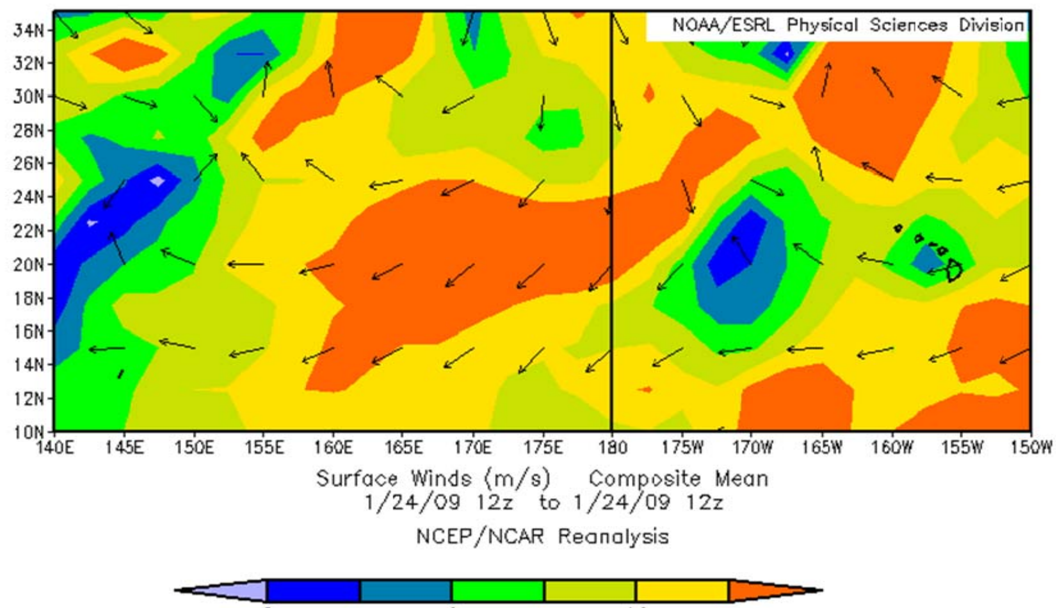



Figure 62. January 2009 wind event; 24 January 00Z, 06Z (ESRL, 2010).



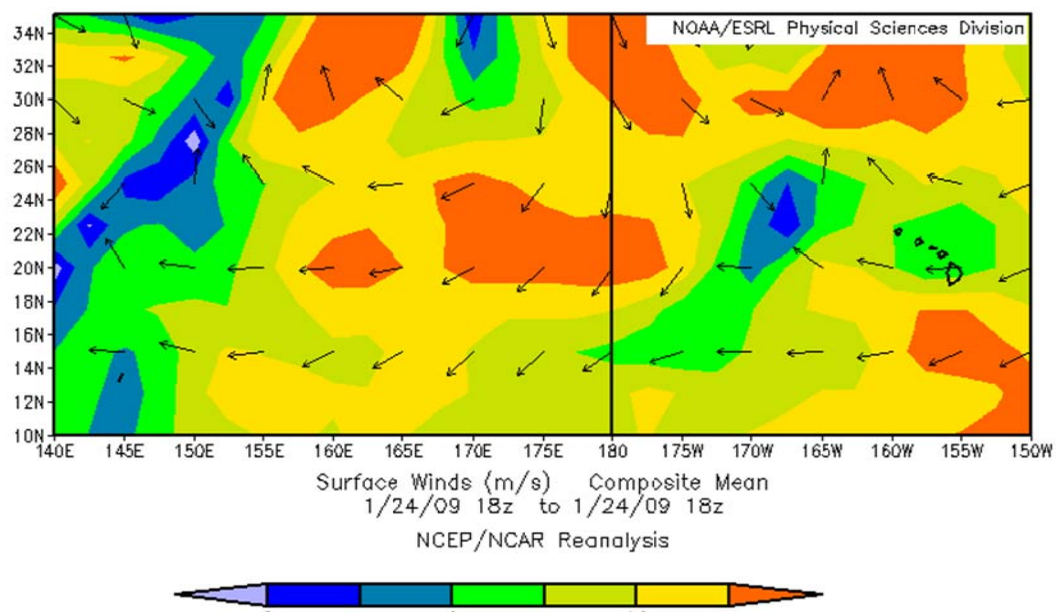




Figure 63. January 2009 wind event; 24 January 12Z, 18Z (ESRL, 2010).

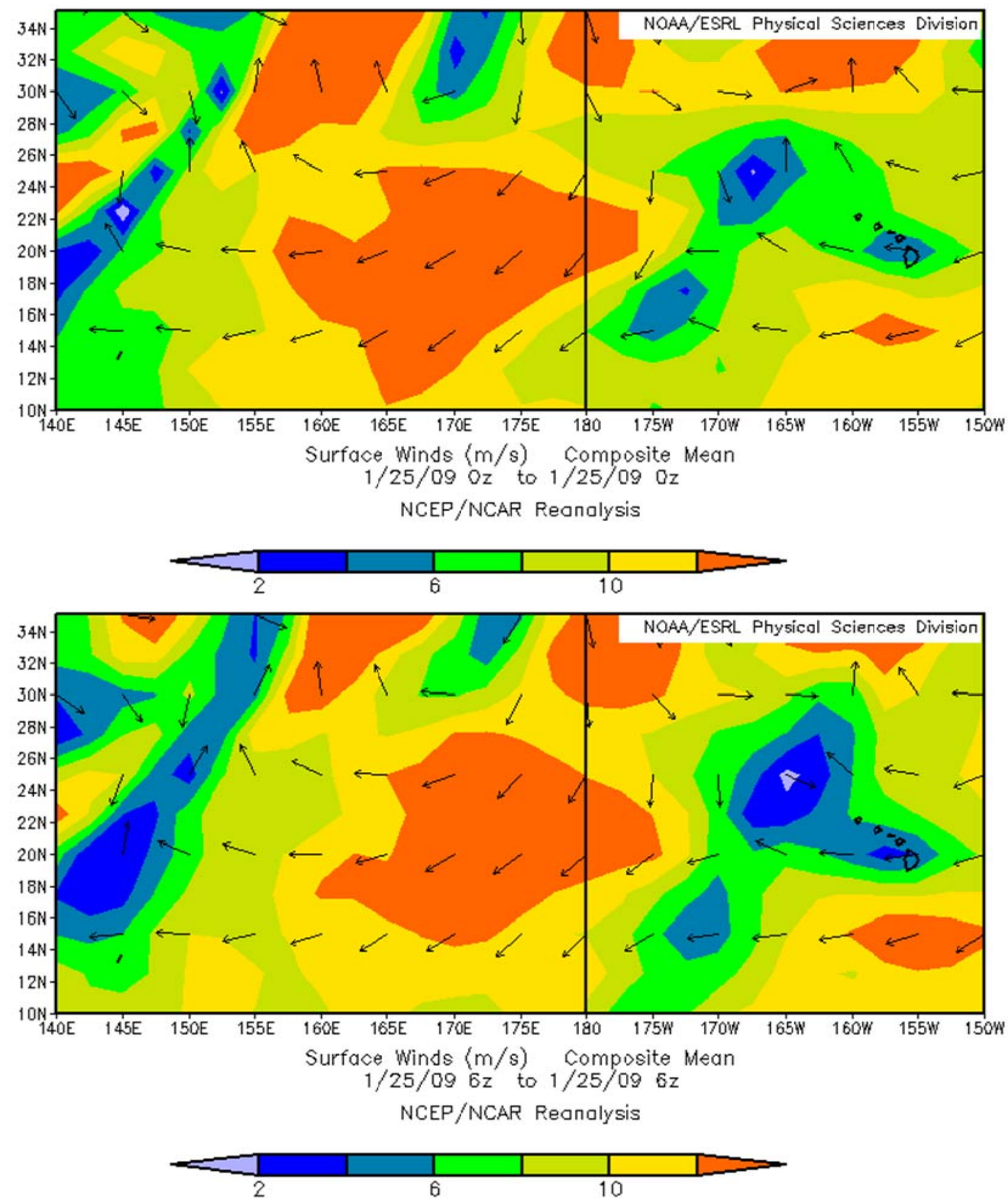



Figure 64. January 2009 wind event; 25 January 00Z, 06Z (ESRL, 2010).

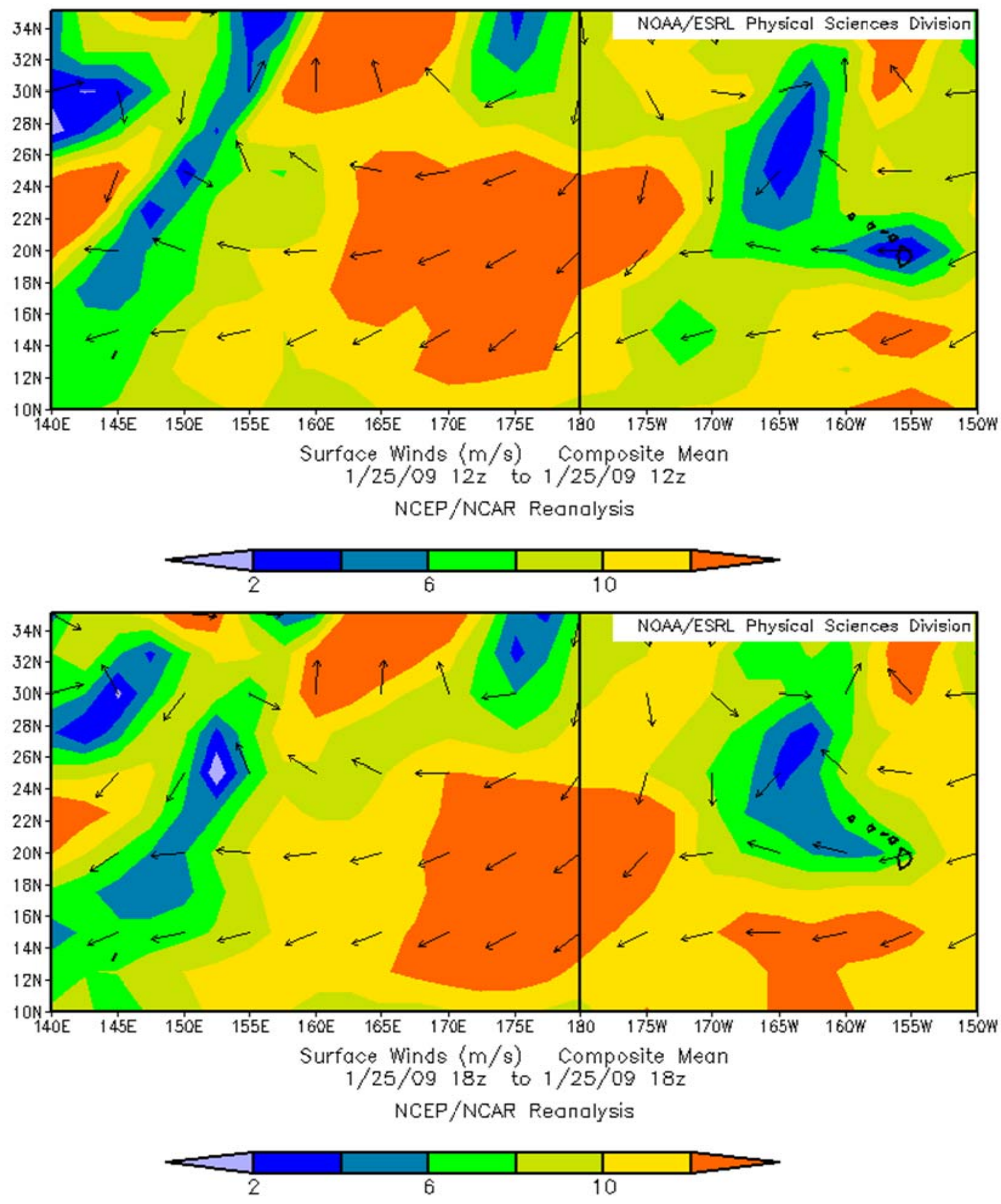



Figure 65. January 2009 wind event; 25 January 12Z, 18Z (ESRL, 2010).

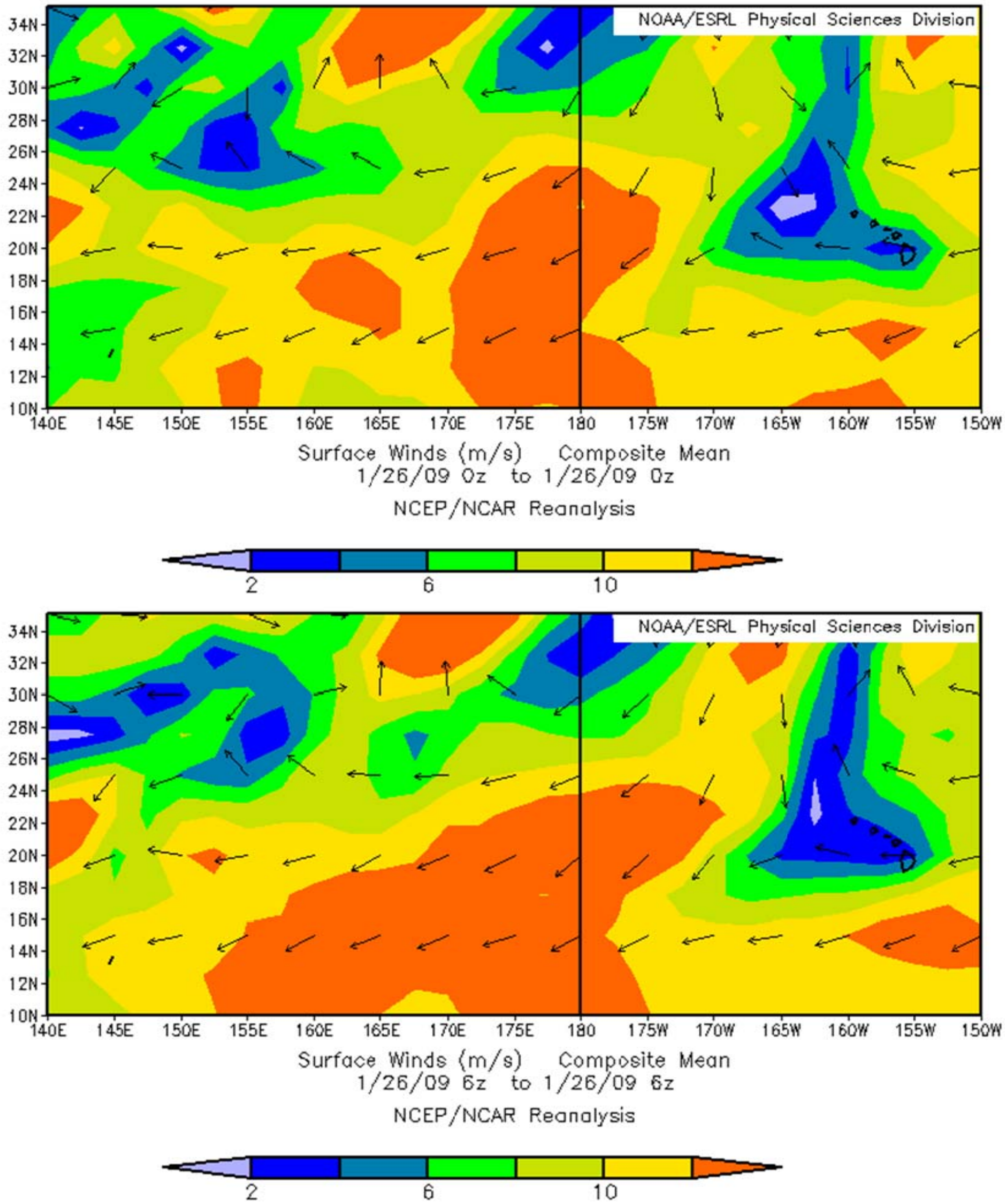



Figure 66. January 2009 wind event; 26 January 00Z, 06Z (ESRL, 2010).

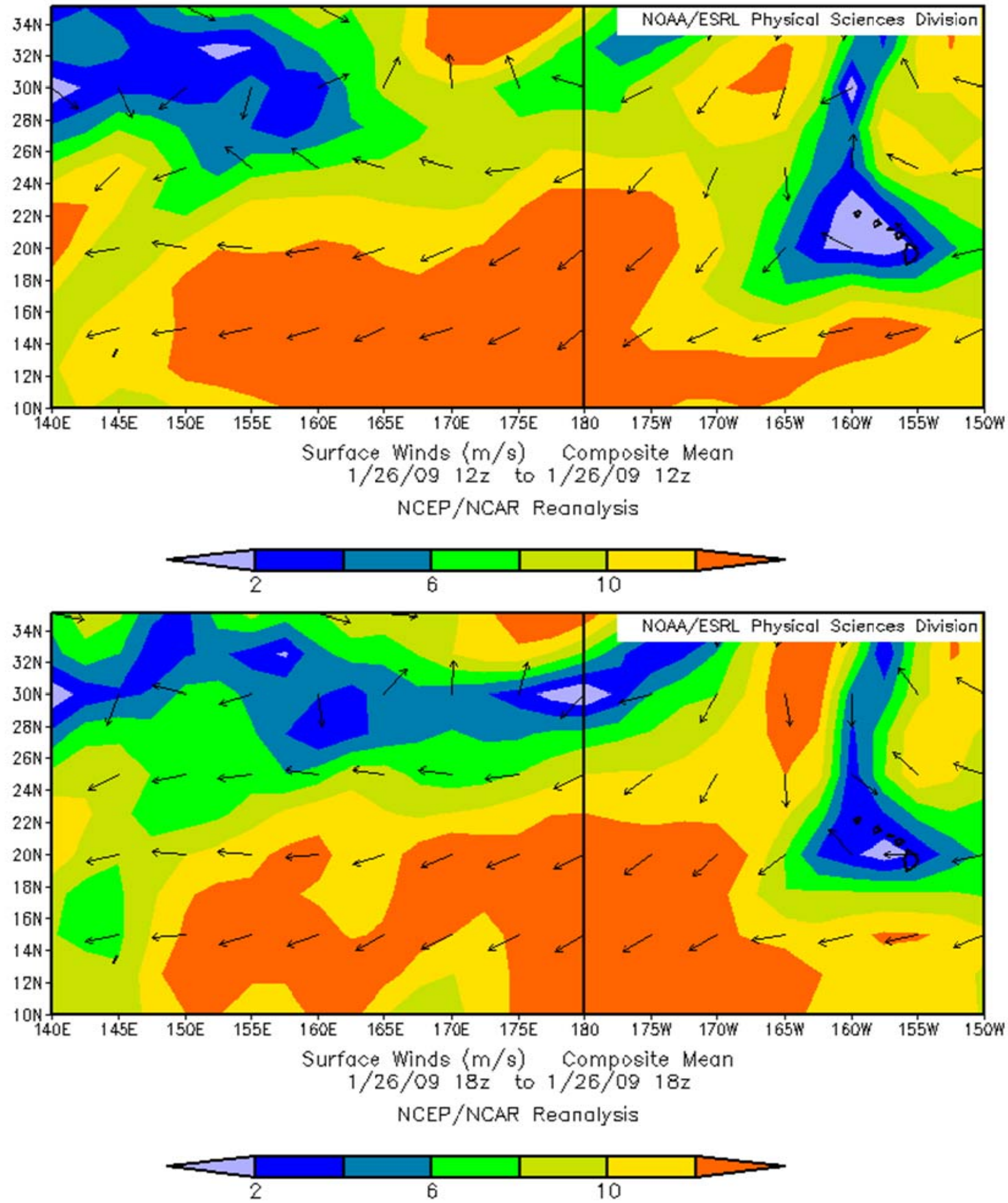



Figure 67. January 2009 wind event; 26 January 12Z, 18Z (ESRL, 2010).

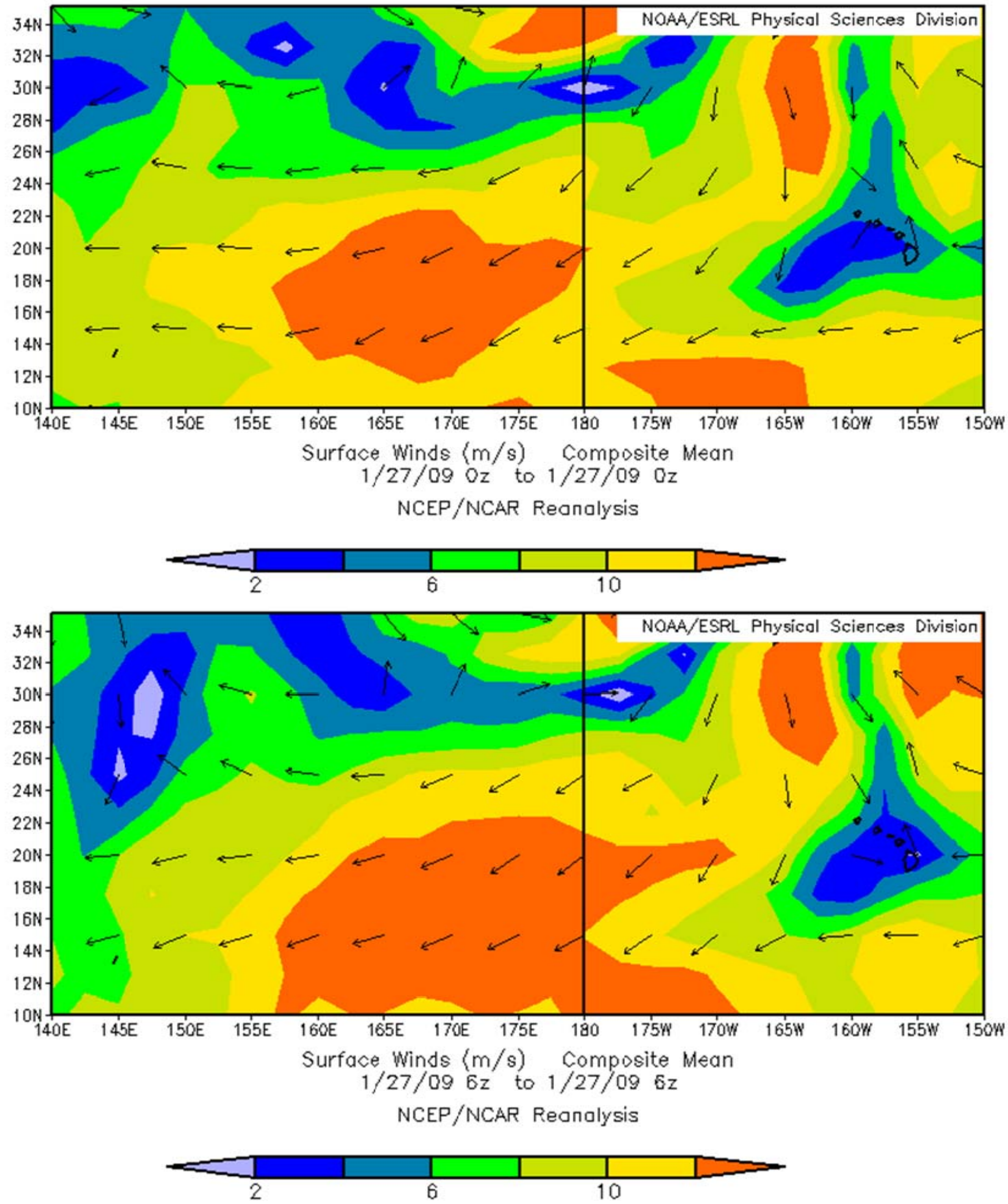



Figure 68. January 2009 wind event; 27 January 00Z, 06Z (ESRL, 2010).

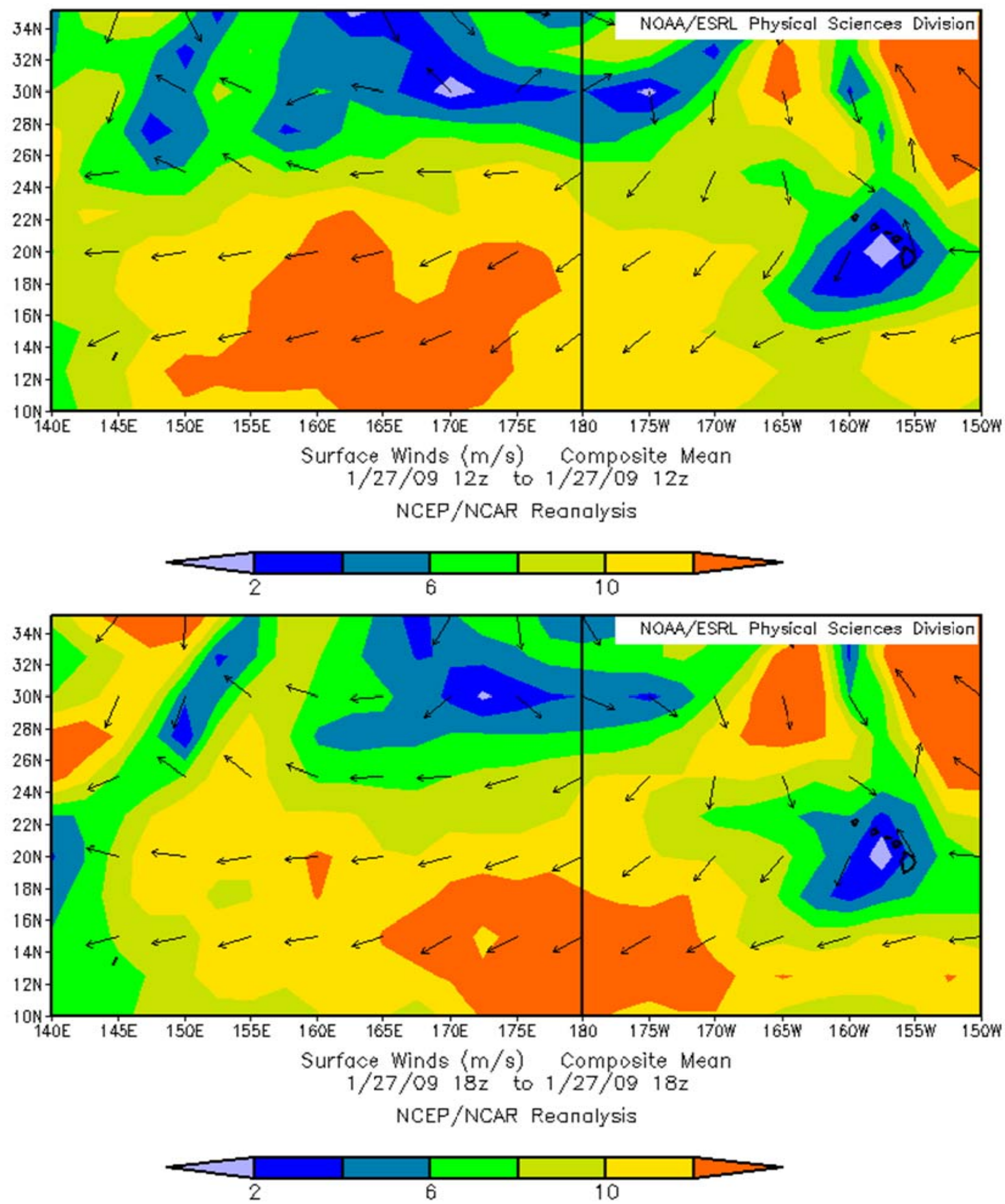



Figure 69. January 2009 wind event; 27 January 12Z, 18Z (ESRL, 2010).

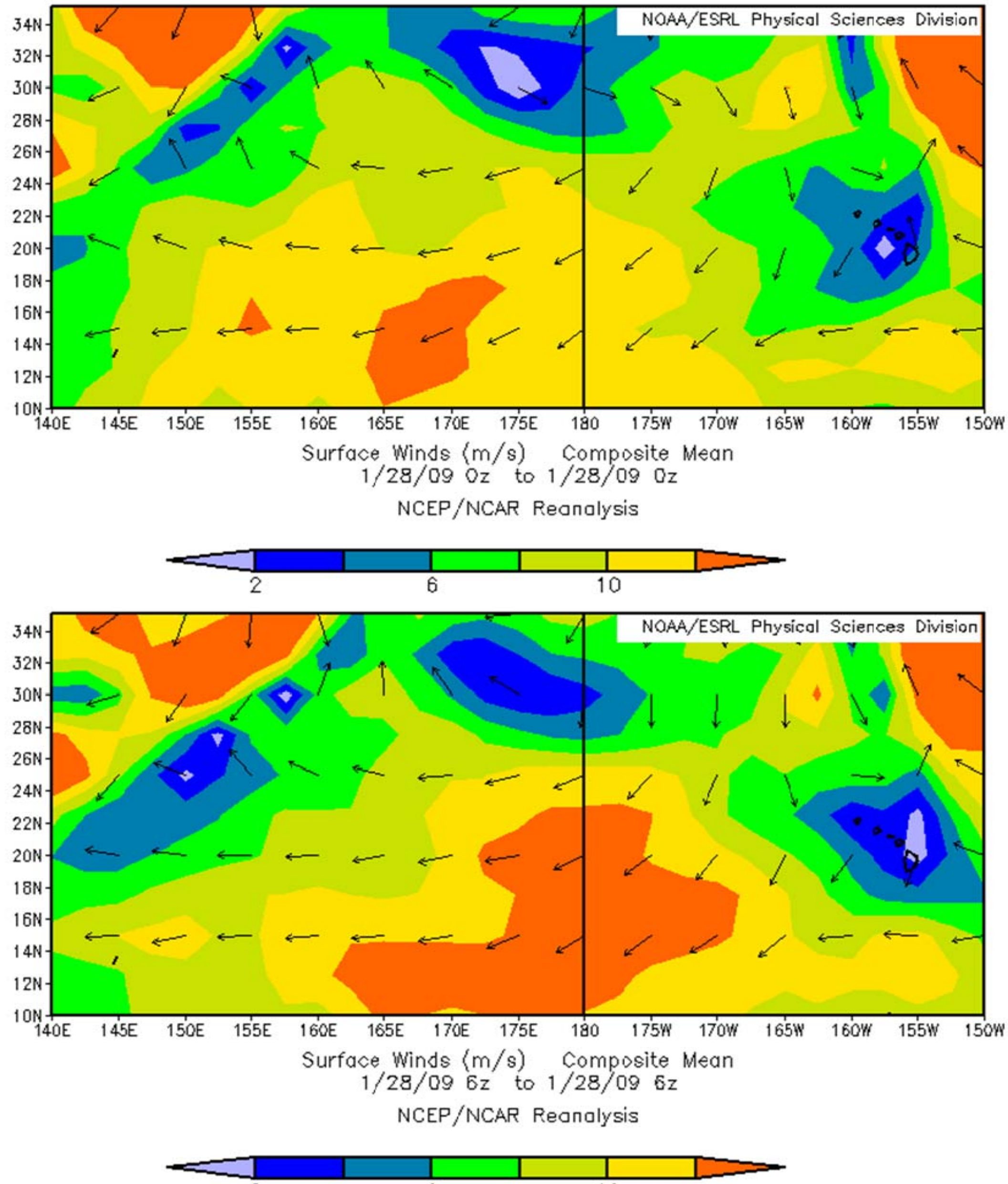



Figure 70. January 2009 wind event; 28 January 00Z, 06Z (ESRL, 2010).

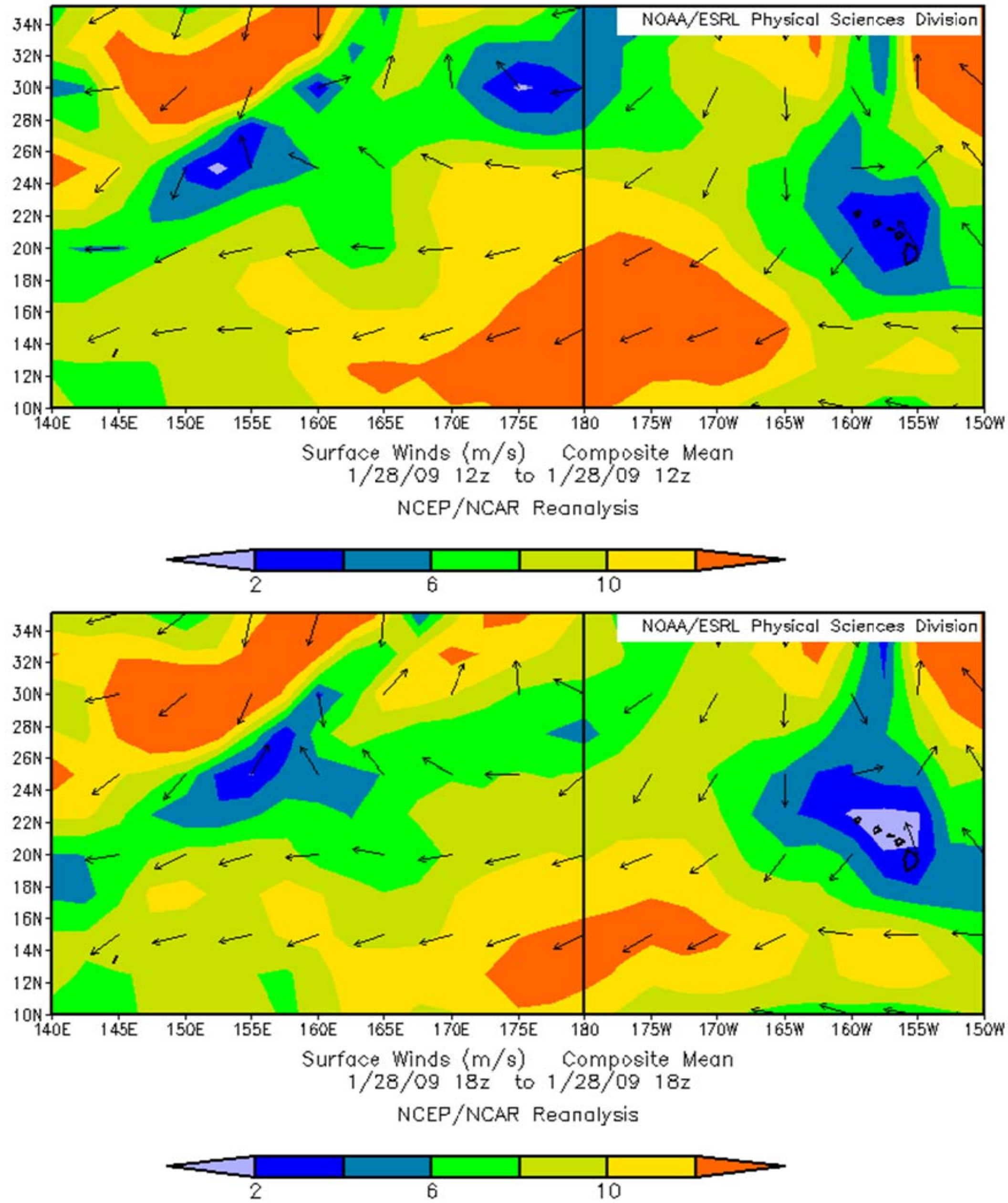



Figure 71. January 2009 wind event; 28 January 12Z, 18Z (ESRL, 2010).

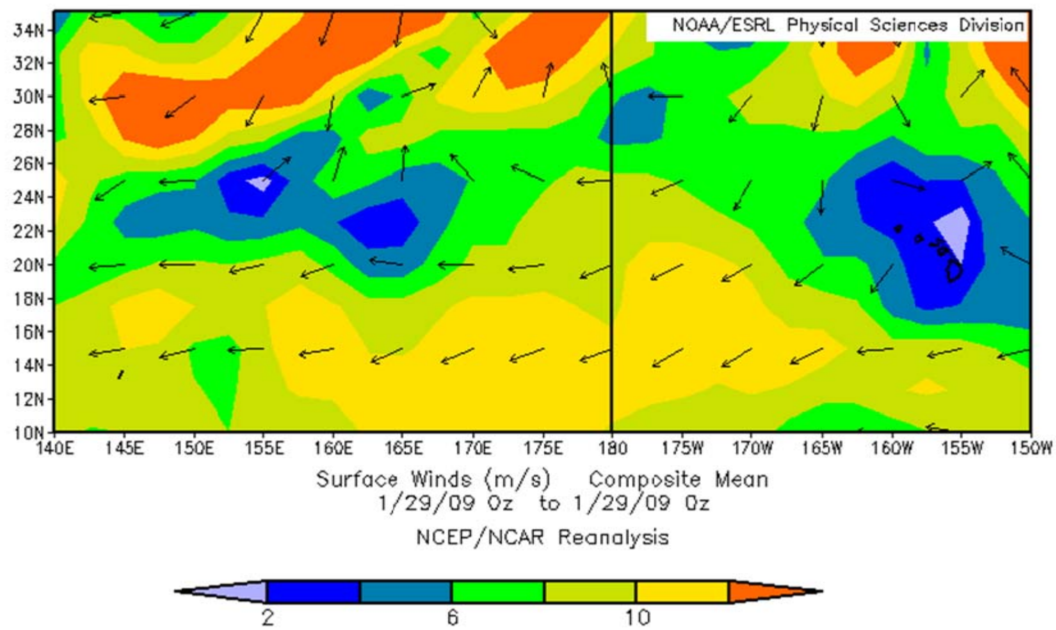



Figure 72. January 2009 wind event; 29 January 00Z (ESRL, 2010).

## C. NOVEMBER 2009

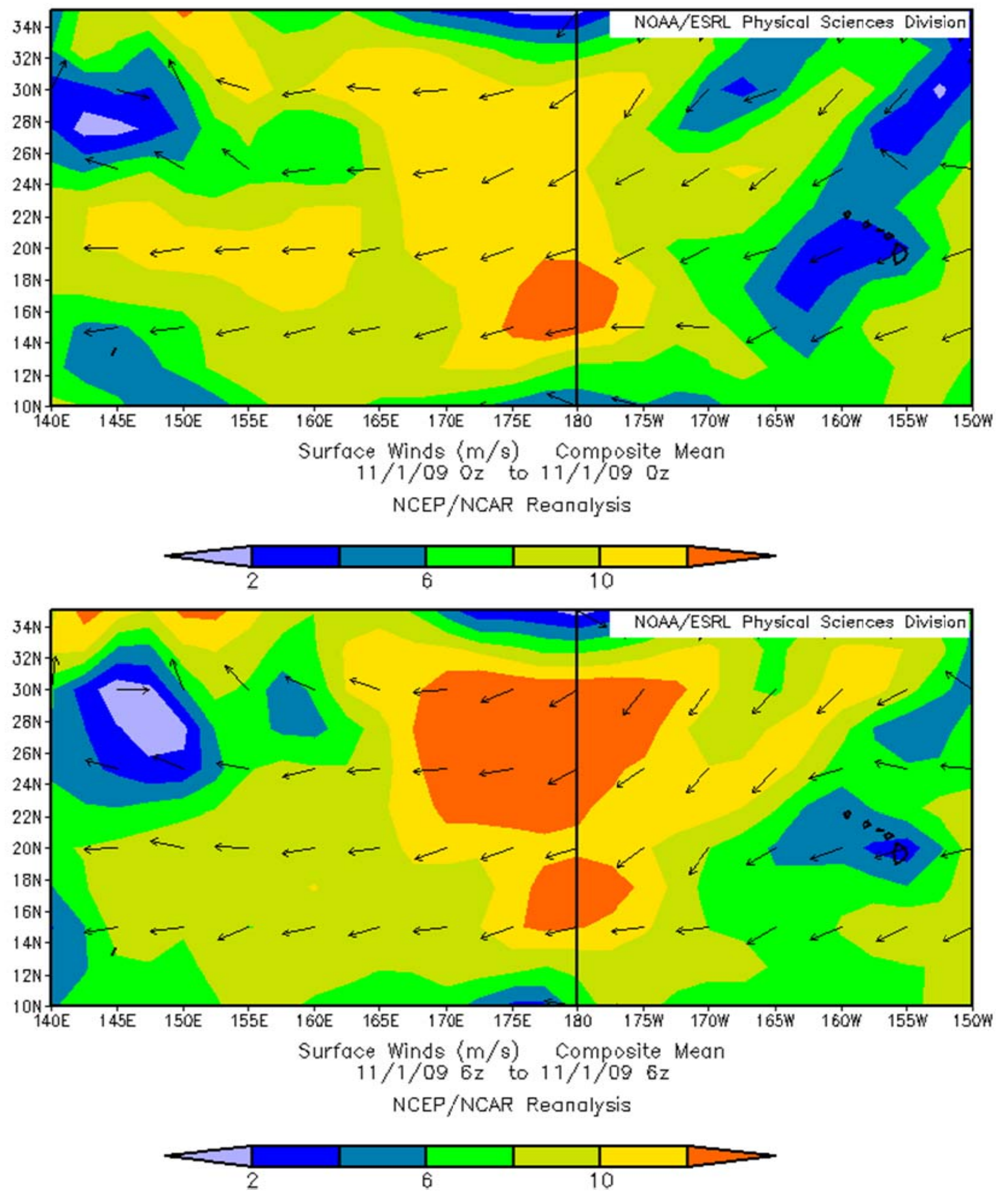



Figure 73. November 2009 wind event; 1 November 00Z, 06Z (ESRL, 2010).

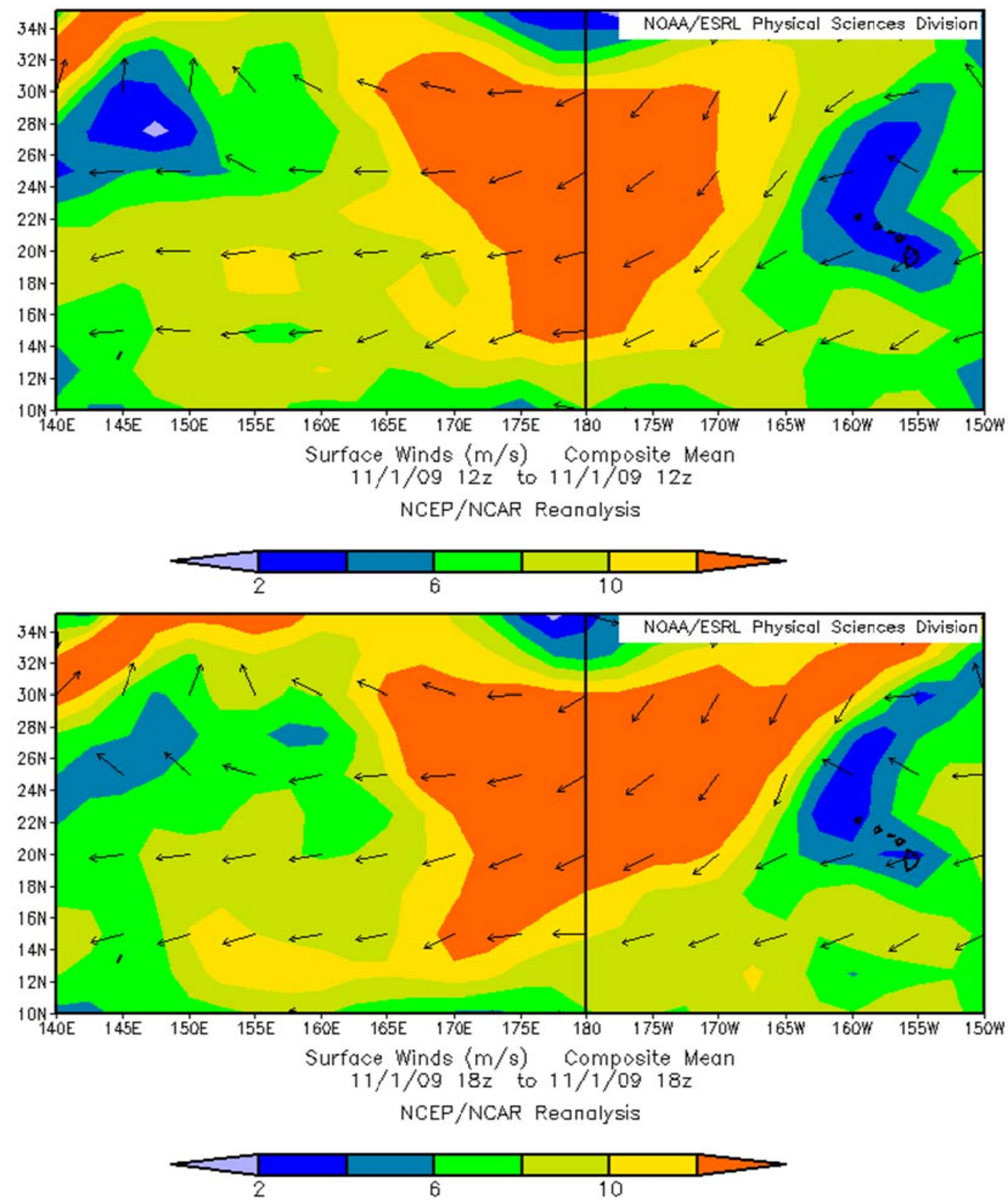



Figure 74. November 2009 wind event; 1 November 12Z, 18Z (ESRL, 2010).

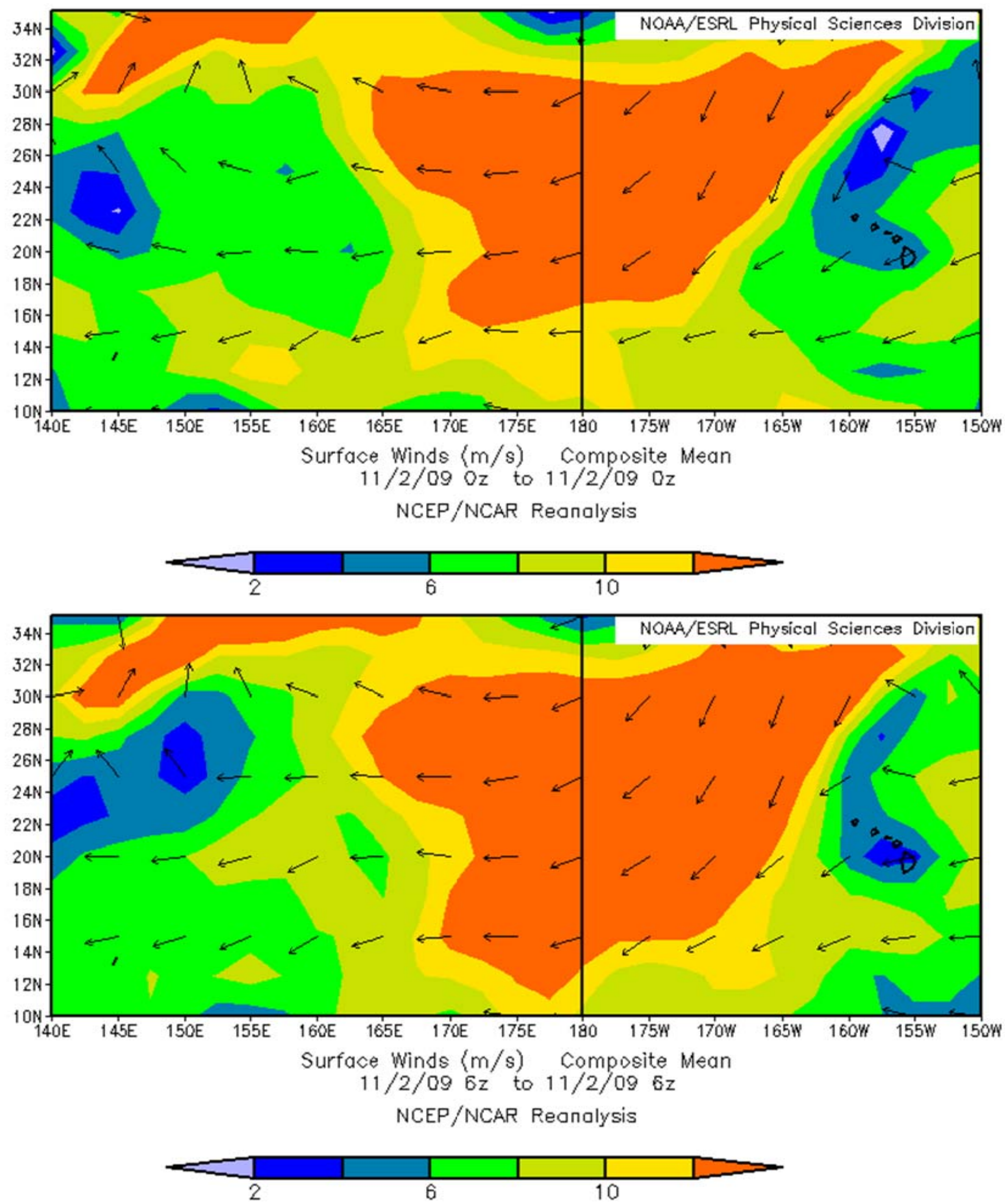



Figure 75. November 2009 wind event; 2 November 00Z, 06Z (ESRL, 2010).

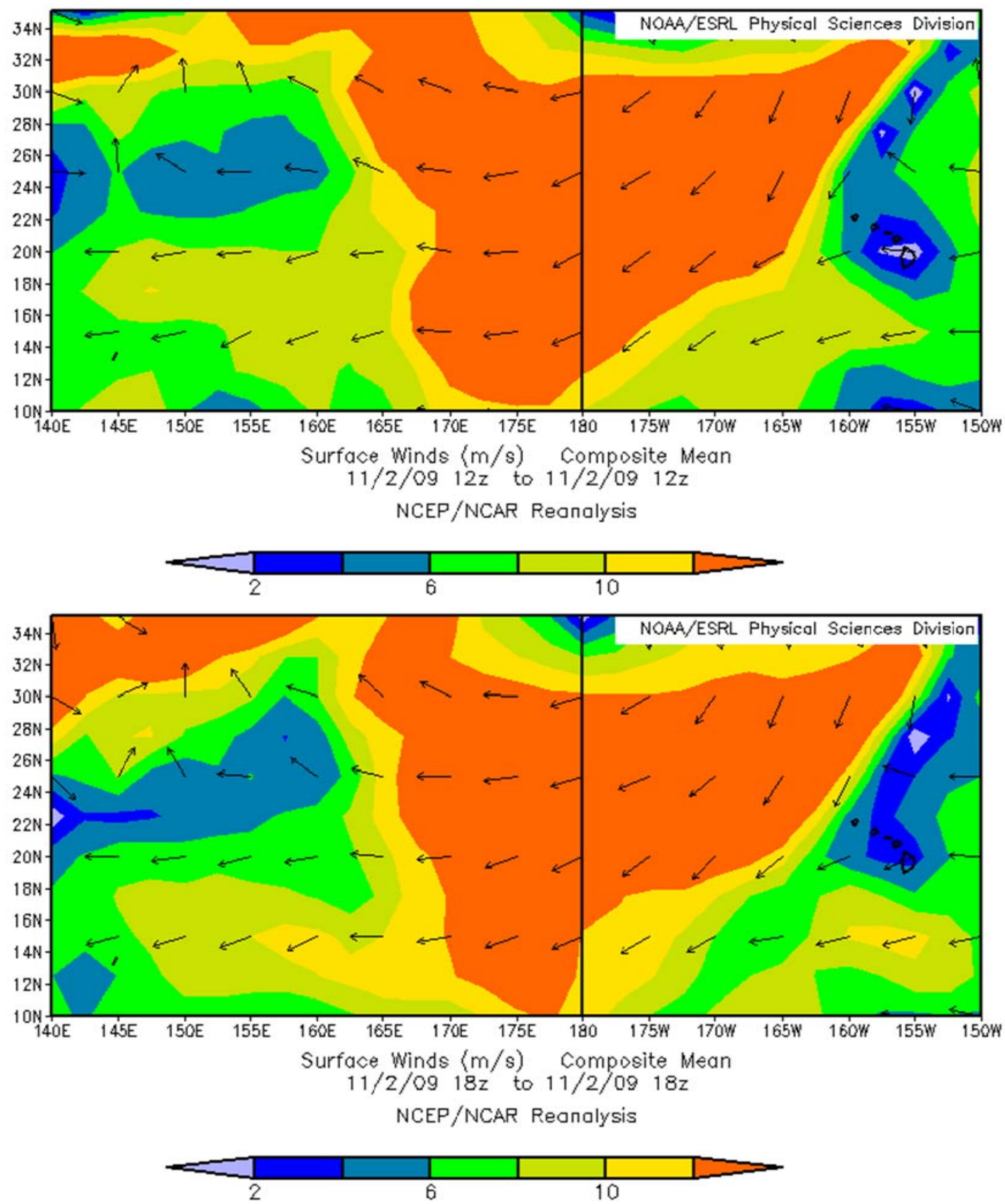



Figure 76. November 2009 wind event; 2 November 12Z, 18Z (ESRL, 2010).

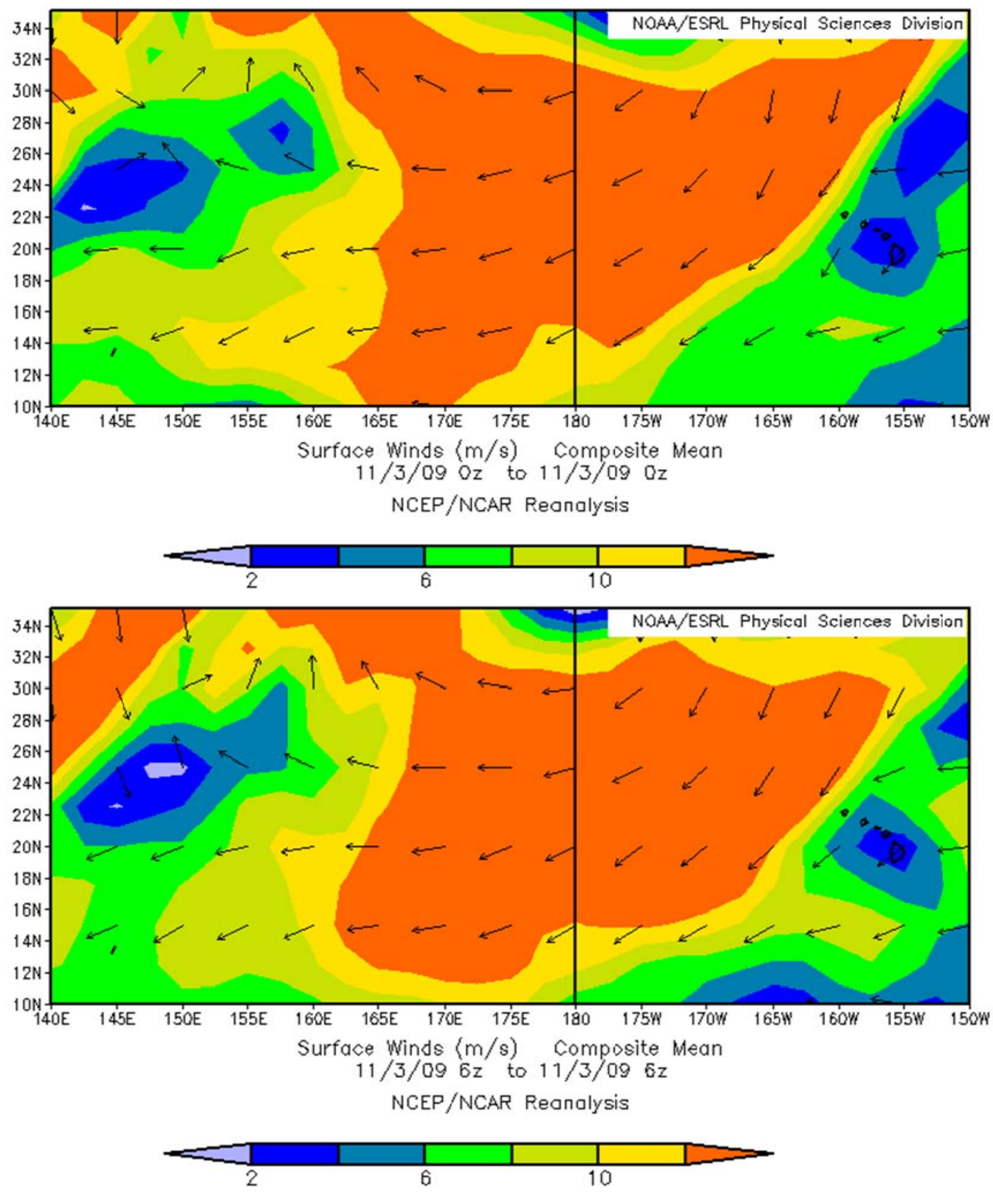



Figure 77. November 2009 wind event; 3 November 00Z, 06Z (ESRL, 2010).

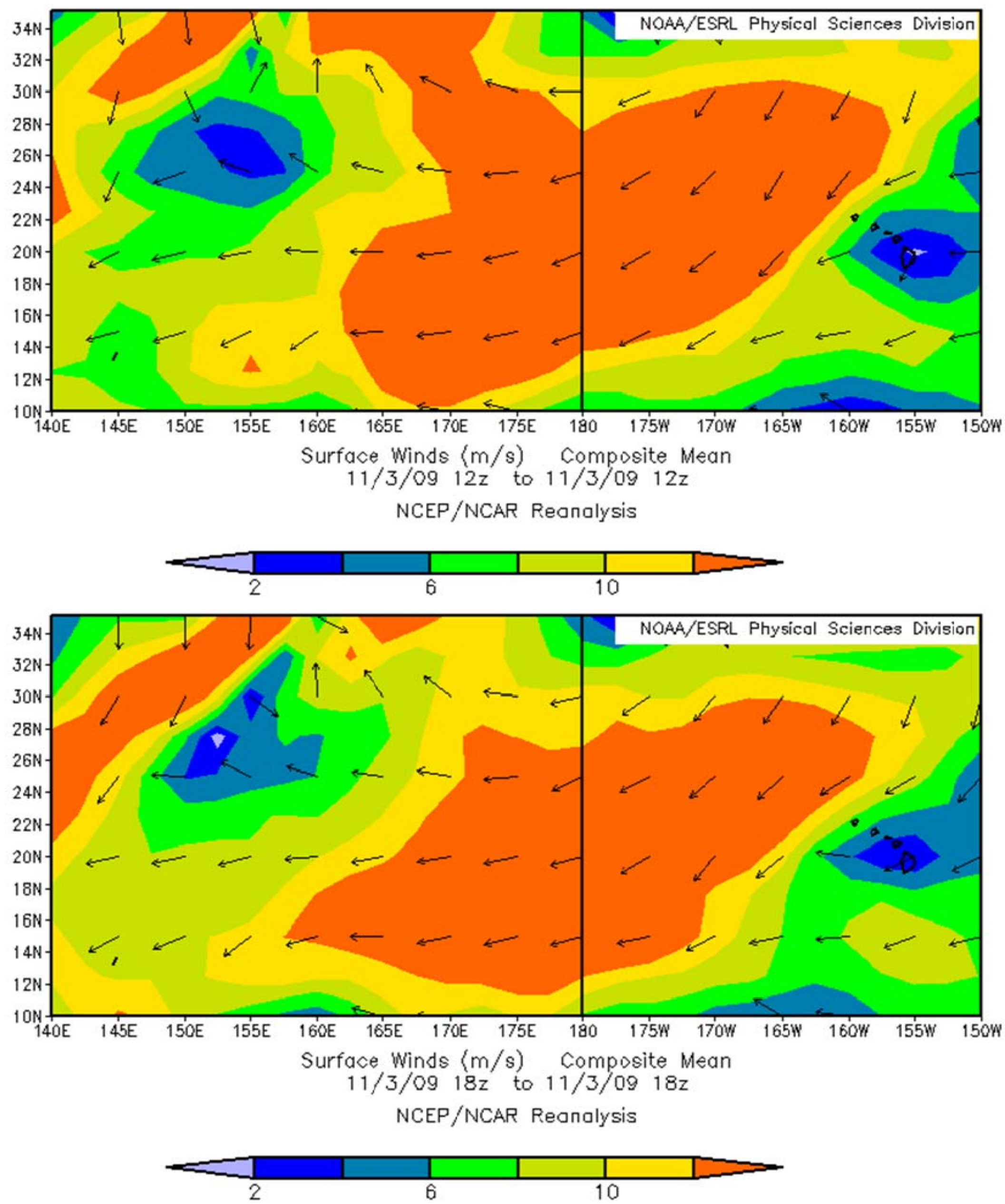



Figure 78. November 2009 wind event; 3 November 12Z, 18Z (ESRL, 2010).

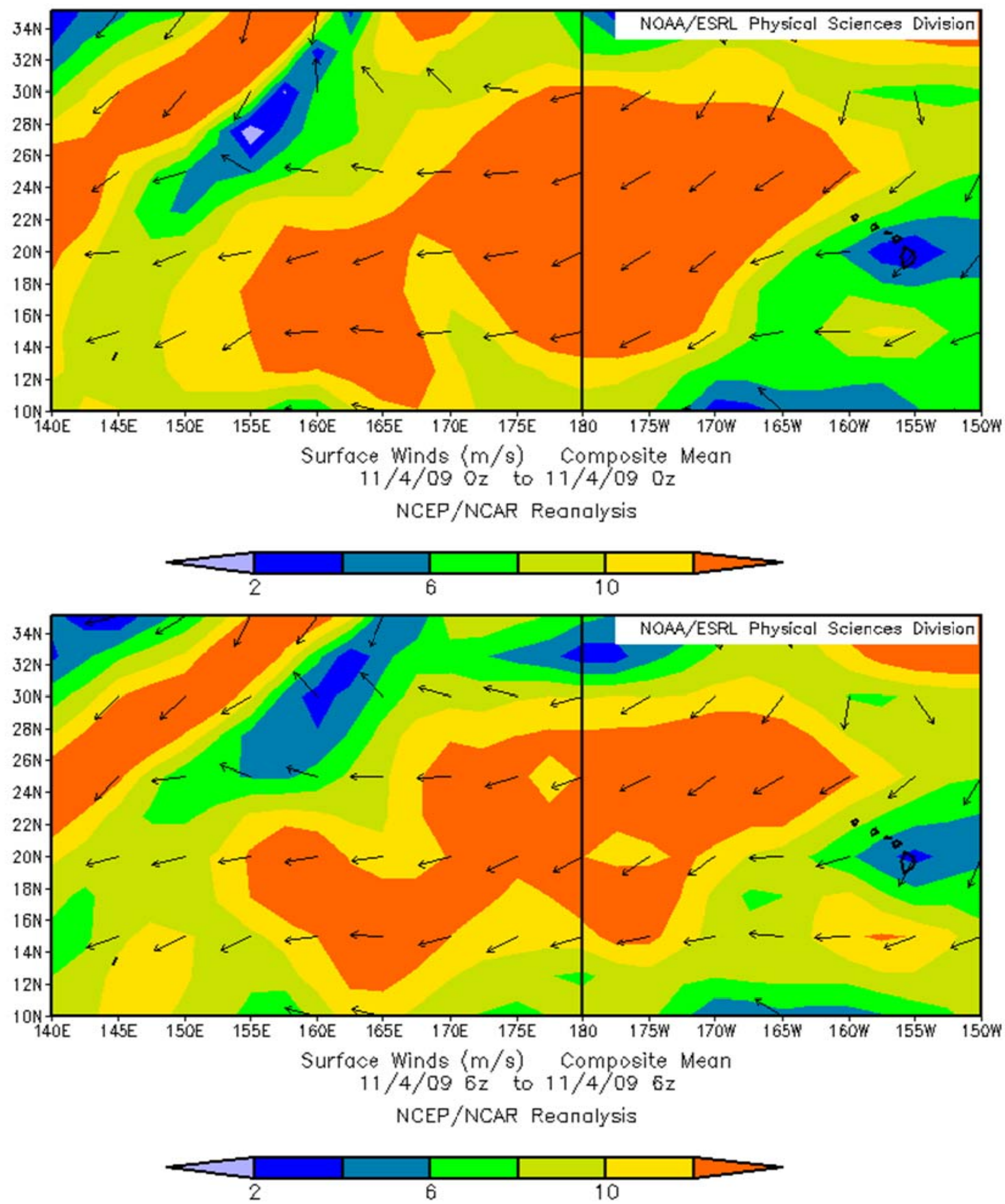



Figure 79. November 2009 wind event; 4 November 00Z, 06Z (ESRL, 2010).

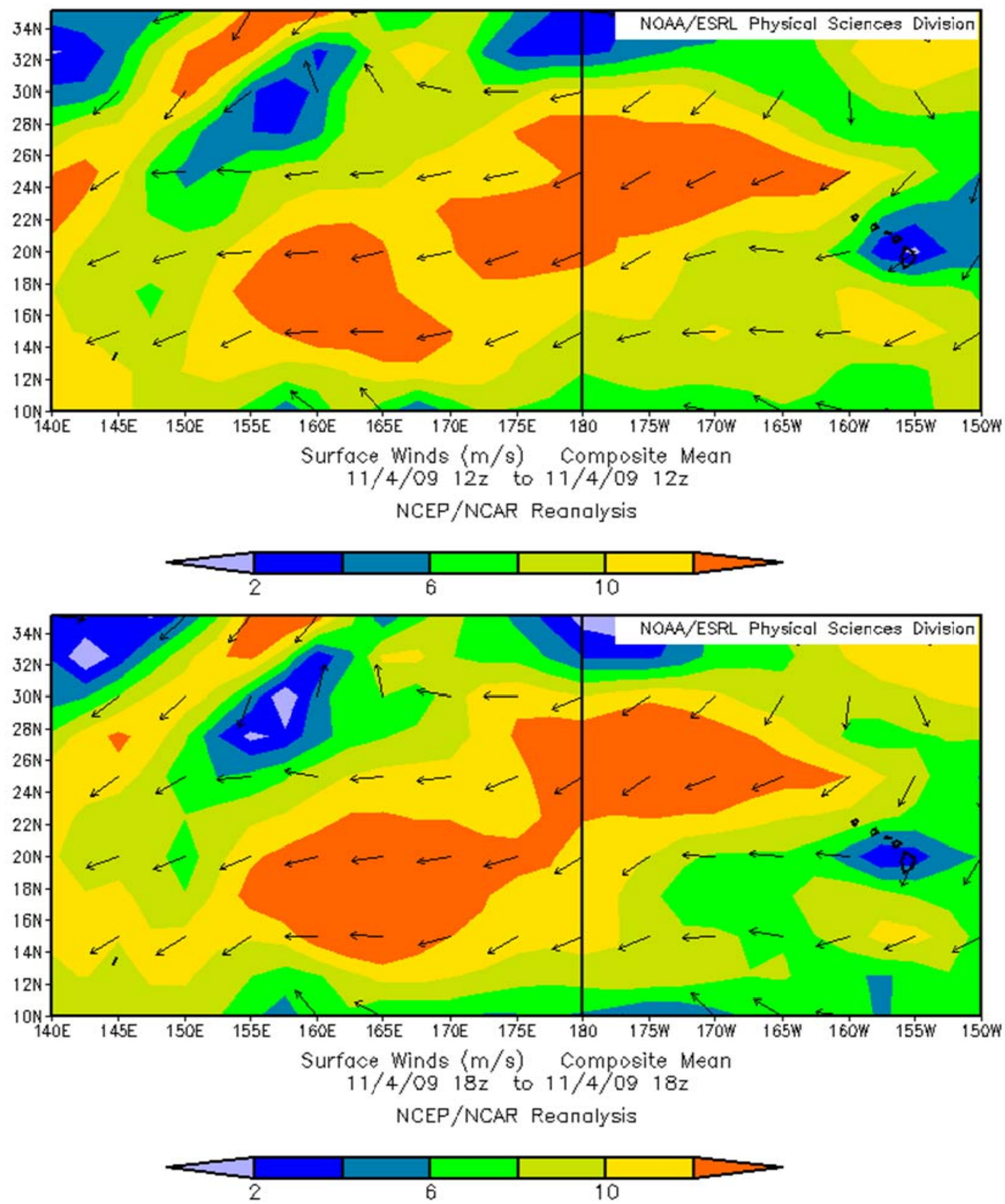



Figure 80. November 2009 wind event; 4 November 12Z, 18Z (ESRL, 2010).

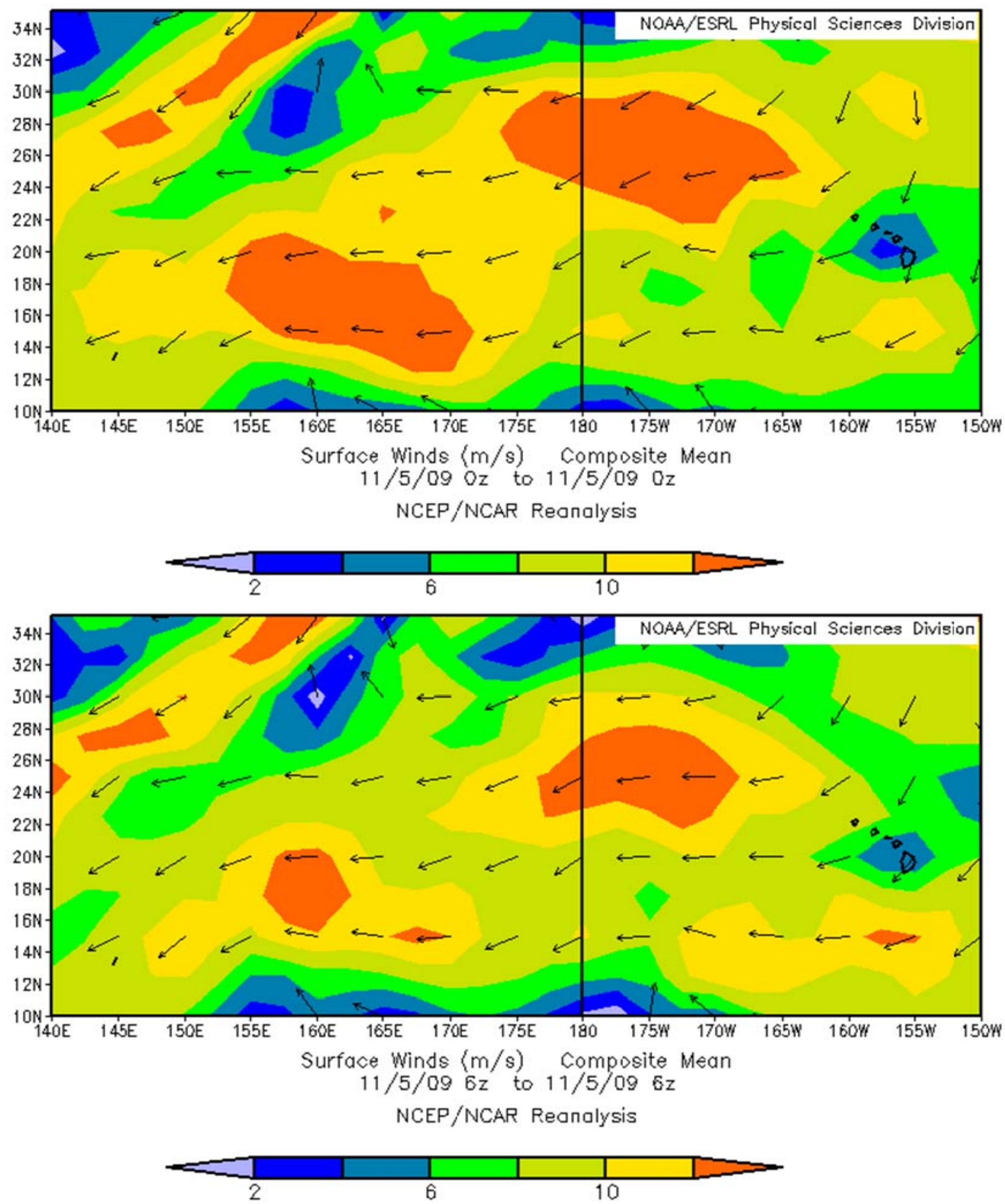



Figure 81. November 2009 wind event; 5 November 00Z, 06Z (ESRL, 2010).

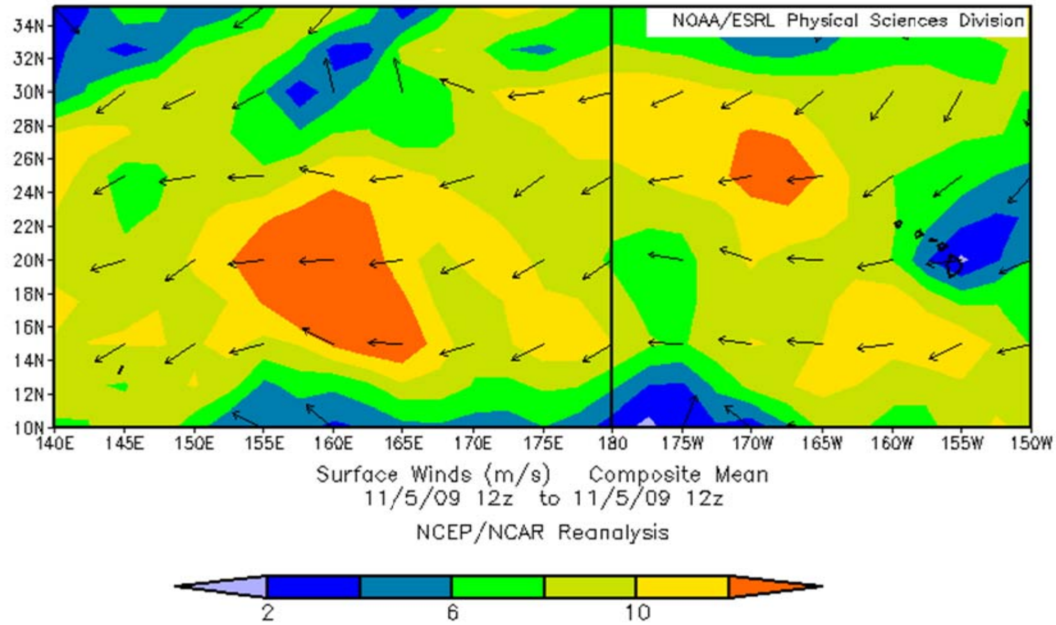



Figure 82. November 2009 wind event; 5 November 12Z (ESRL, 2010).

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## APPENDIX C: PROBABILITY MAP EXAMPLES

### A. JANUARY 2009

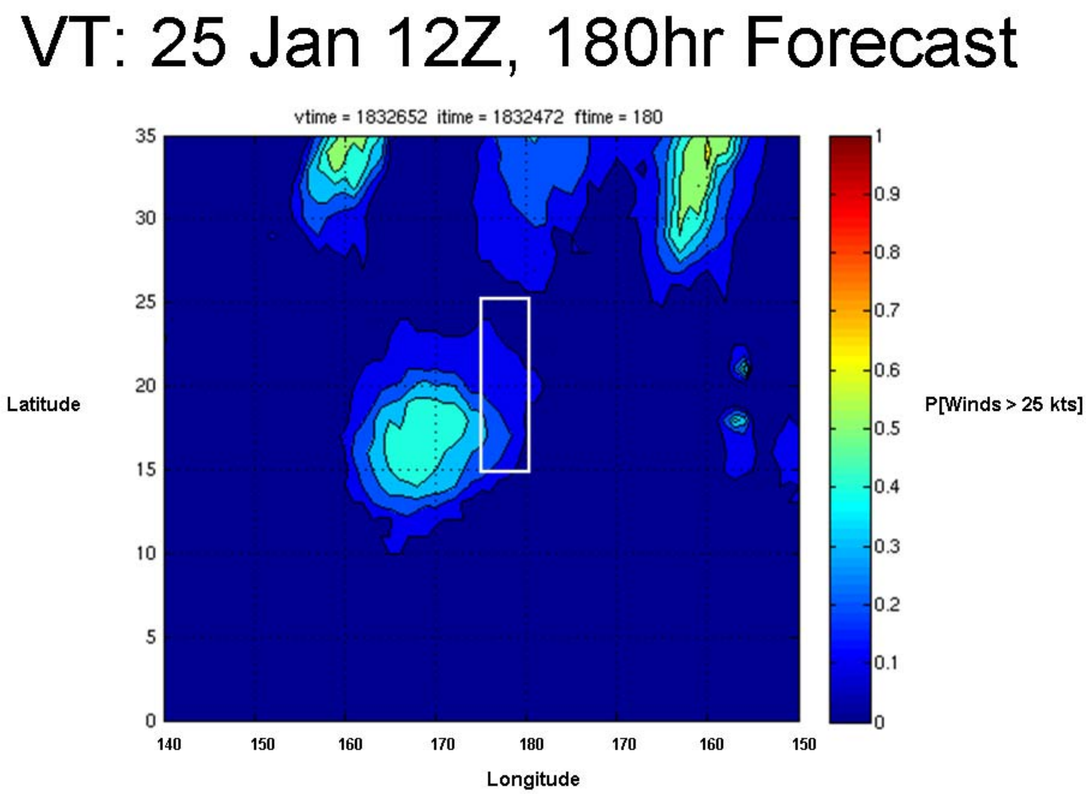


Figure 83. Probability map for valid time 25 January, 12Z; 180 hr forecast.

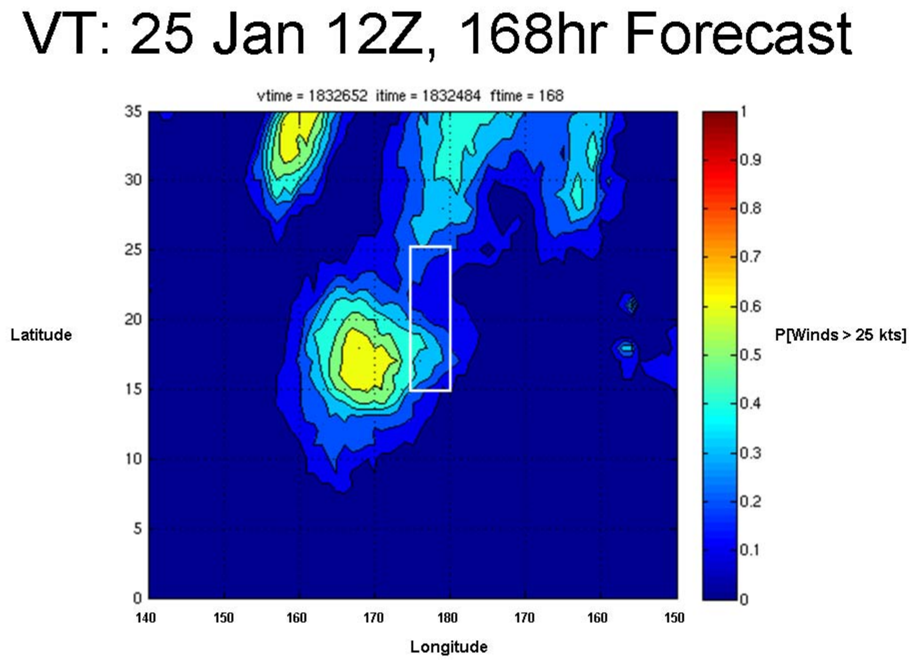


Figure 84. Probability map for valid time 25 January, 12Z; 168 hr forecast.

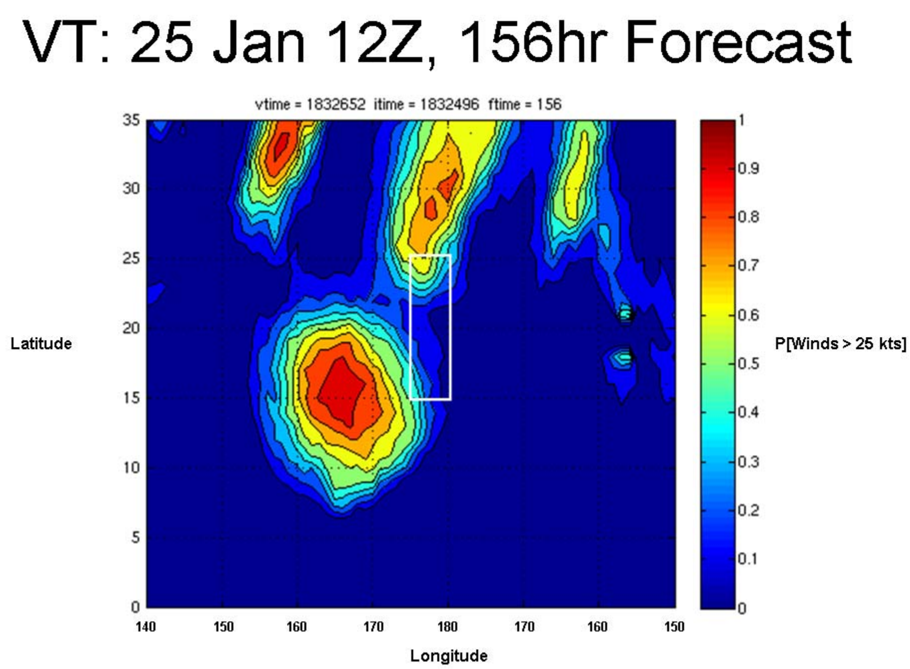


Figure 85. Probability map for valid time 25 January, 12Z; 156 hr forecast.

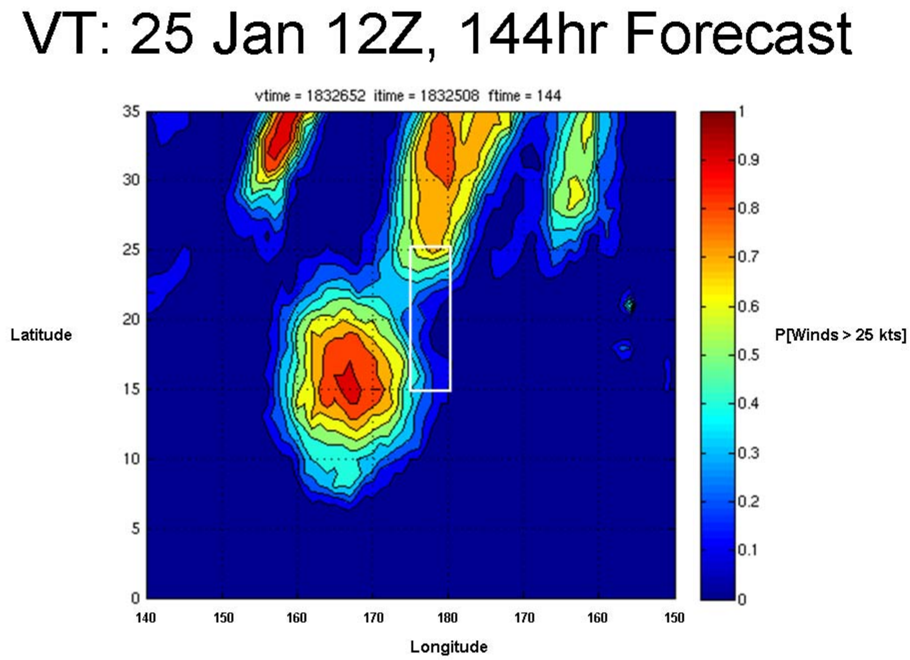


Figure 86. Probability map for valid time 25 January, 12Z; 144 hr forecast.

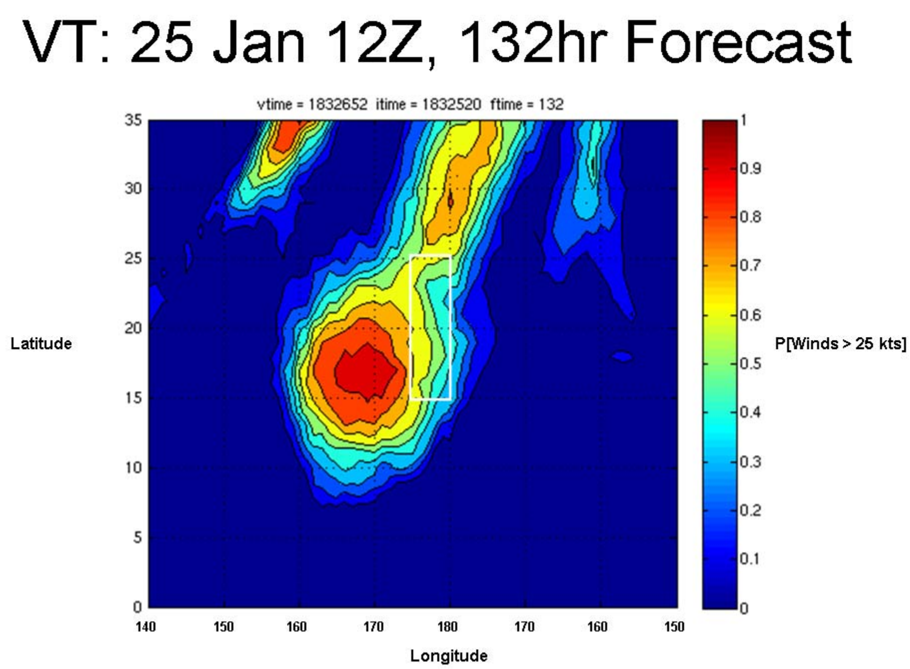


Figure 87. Probability map for valid time 25 January, 12Z;132 hr forecast.

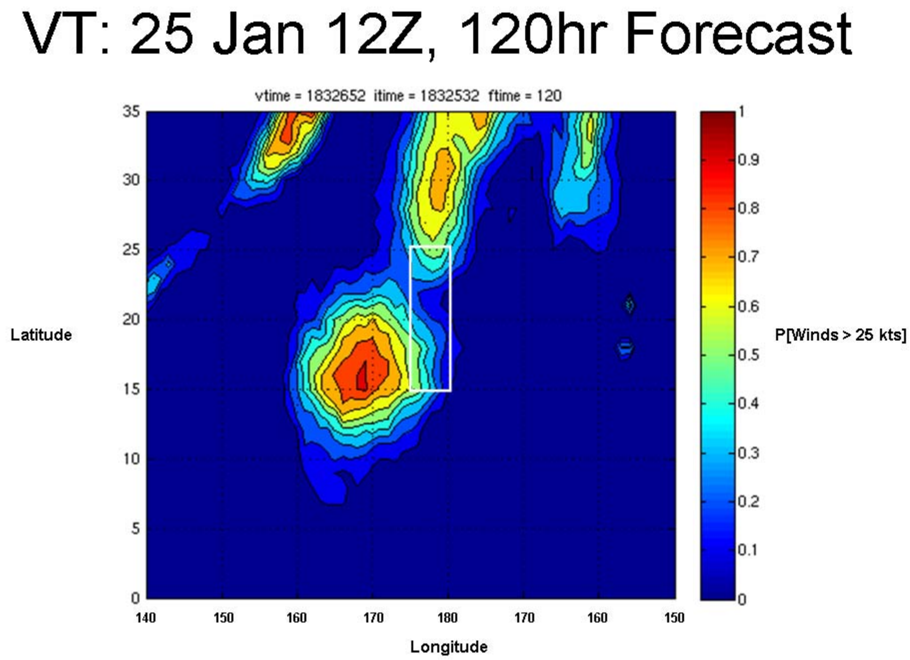


Figure 88. Probability map for valid time 25 January, 12Z; 120 hr forecast.

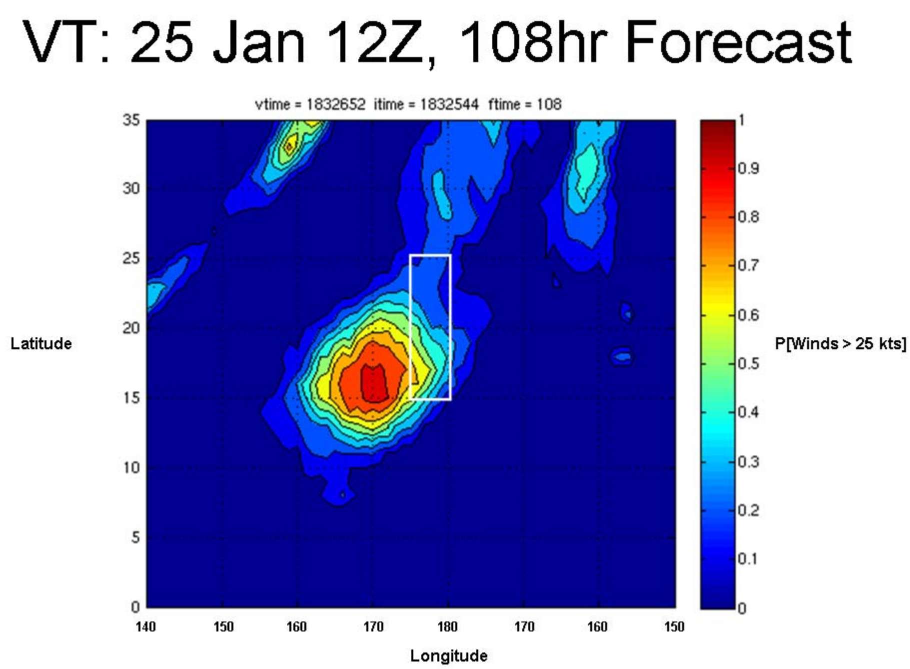


Figure 89. Probability map for valid time 25 January, 12Z; 108 hr forecast.

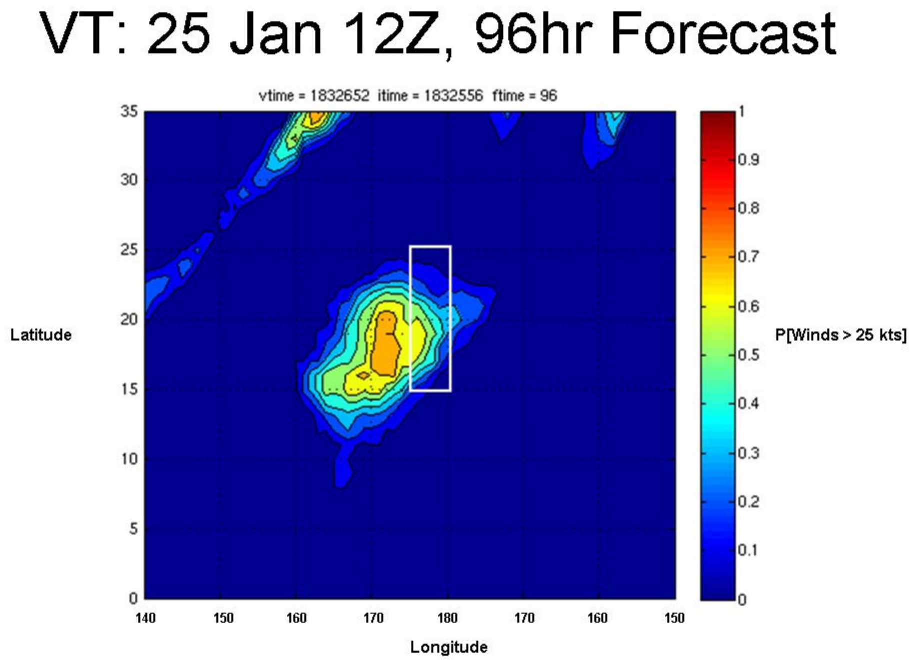


Figure 90. Probability map for valid time 25 January, 12Z; 96 hr forecast.

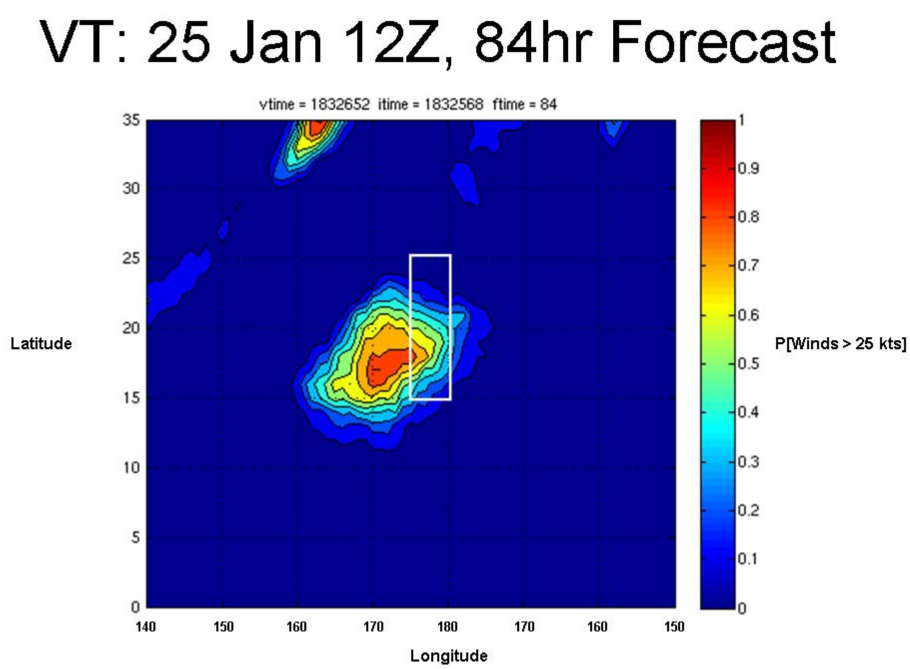


Figure 91. Probability map for valid time 25 January, 12Z; 84 hr forecast.

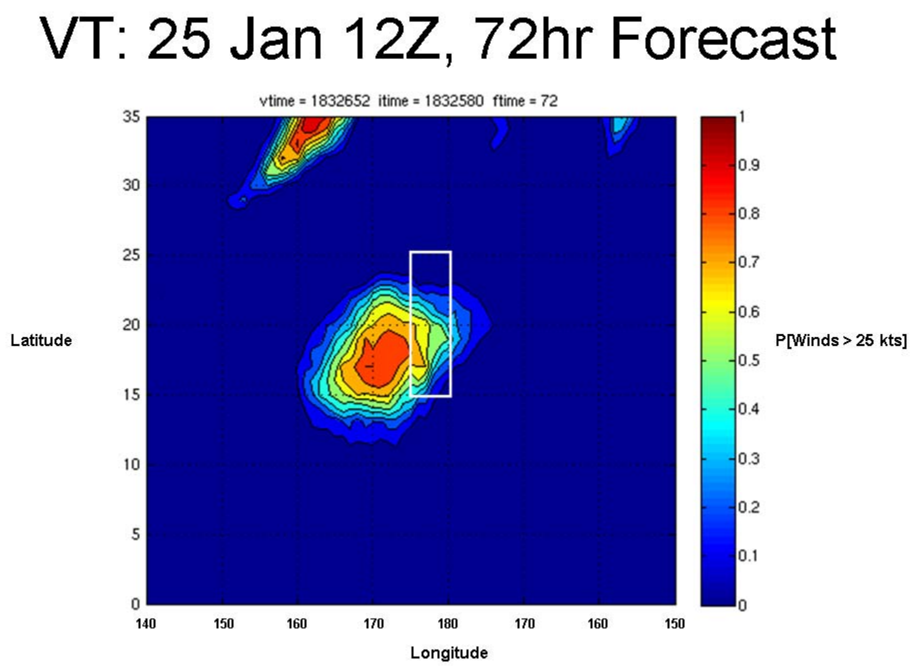


Figure 92. Probability map for valid time 25 January, 12Z; 72 hr forecast.

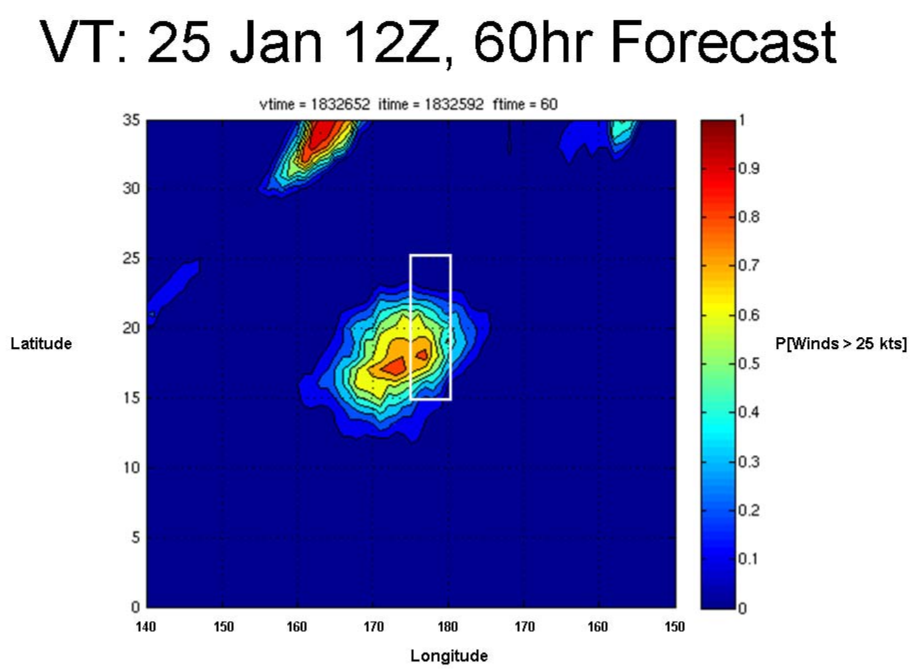


Figure 93. Probability map for valid time 25 January, 12Z; 60 hr forecast.

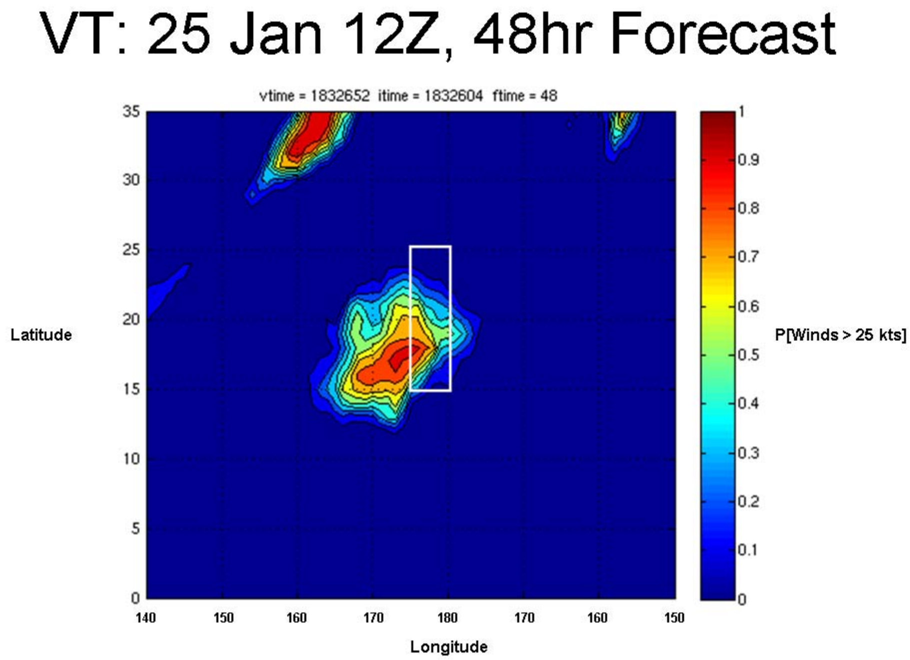


Figure 94. Probability map for valid time 25 January, 12Z; 48 hr forecast.

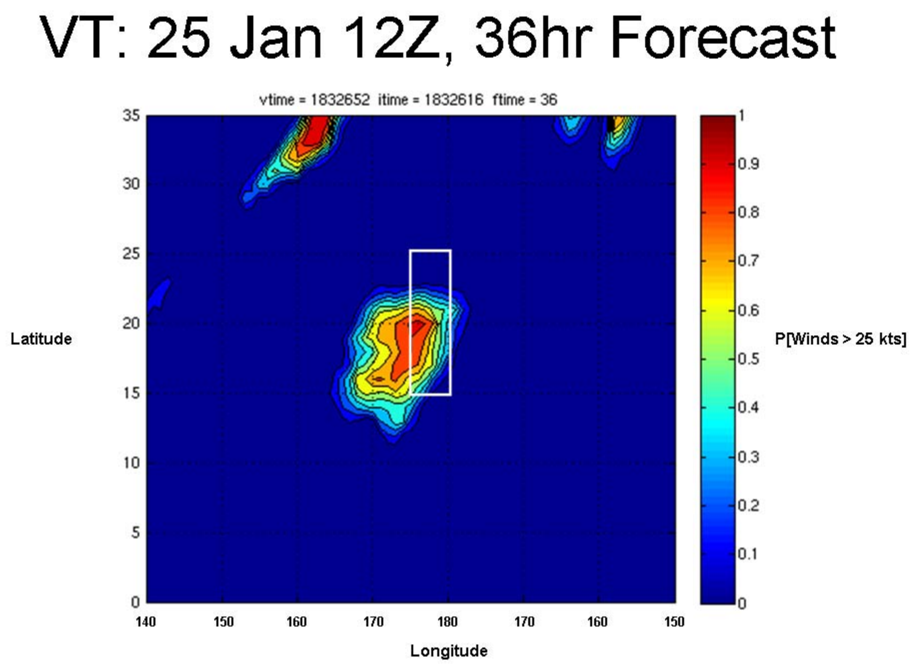


Figure 95. Probability map for valid time 25 January, 12Z; 36 hr forecast.

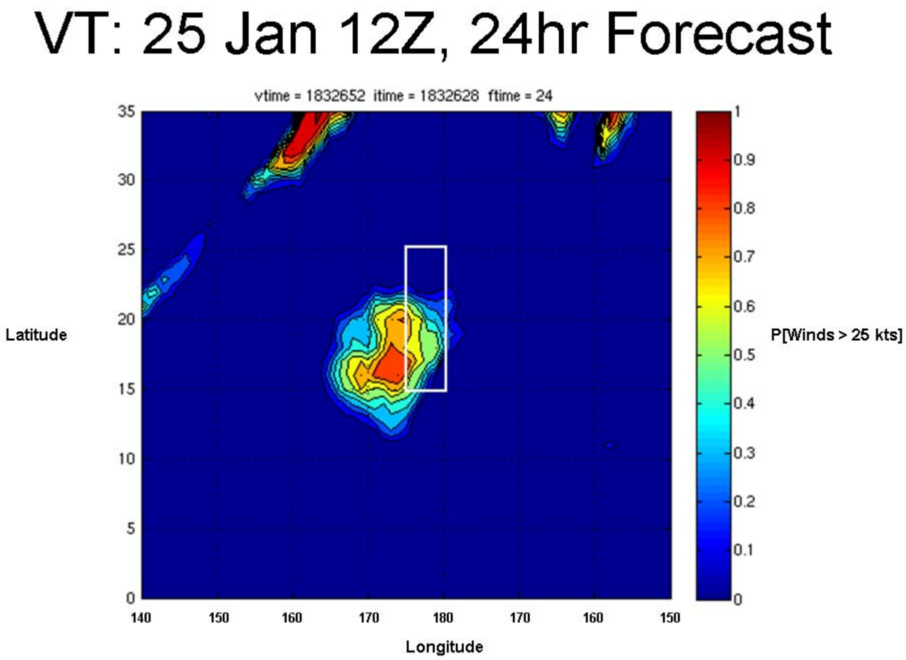


Figure 96. Probability map for valid time 25 January, 12Z; 24 hr forecast.

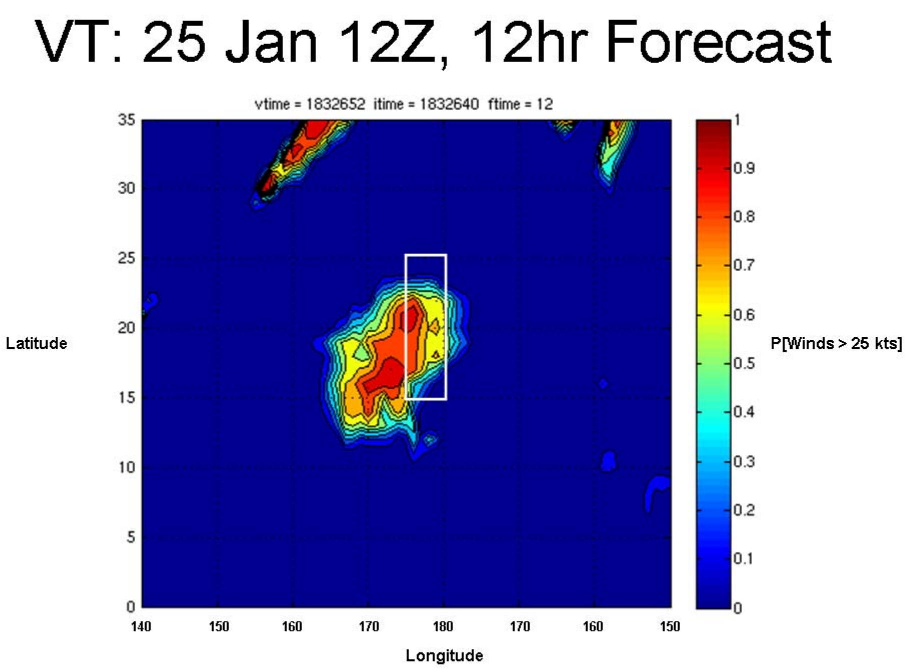


Figure 97. Probability map for valid time 25 January, 12Z; 12 hr forecast.

## B. NOVEMBER 2009

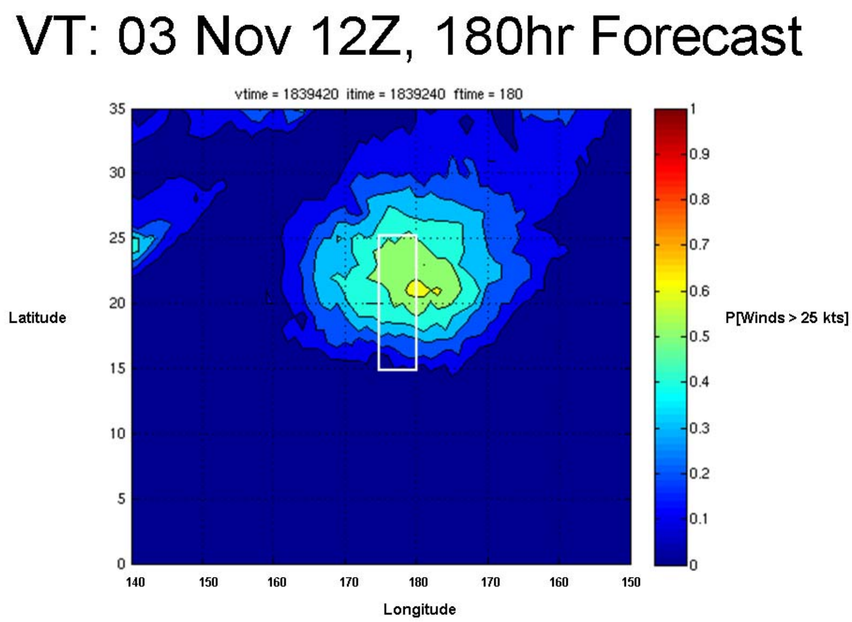


Figure 98. Probability map for valid time 3 November, 12Z; 180 hr forecast.

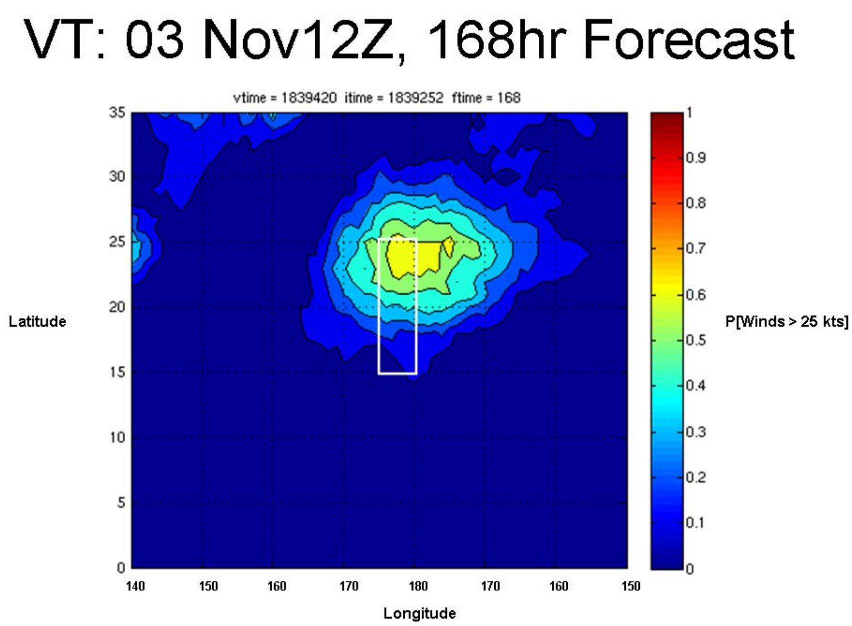


Figure 99. Probability map for valid time 3 November, 12Z; 168 hr forecast.

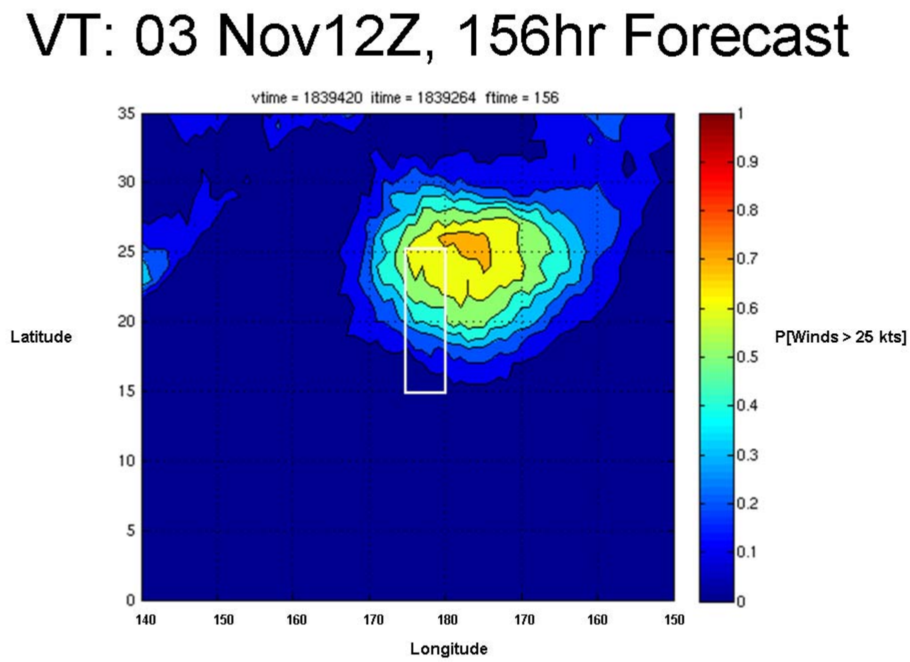


Figure 100. Probability map for valid time 3 November, 12Z; 156 hr forecast.

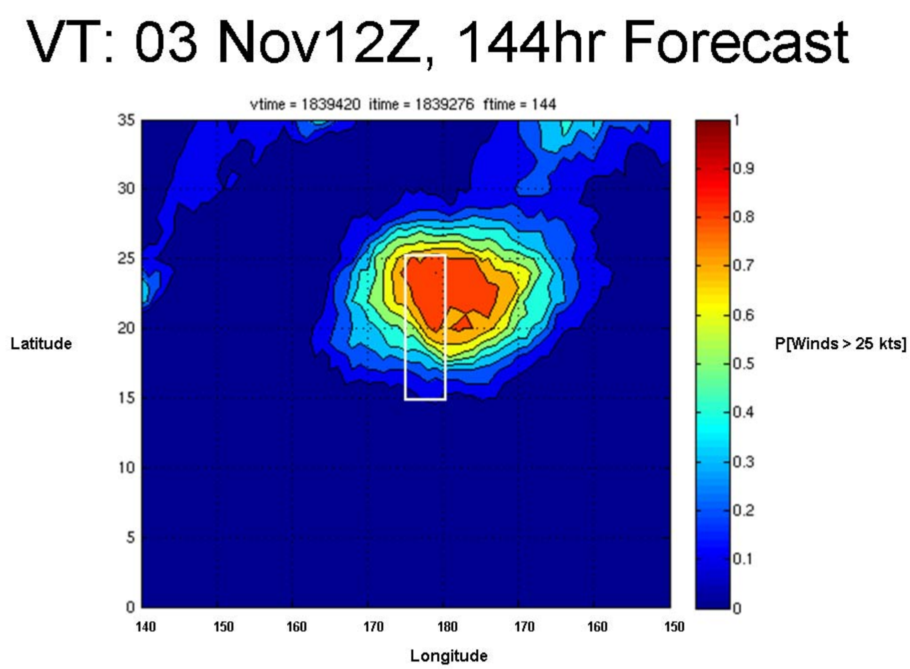


Figure 101. Probability map for valid time 3 November, 12Z; 144 hr forecast.

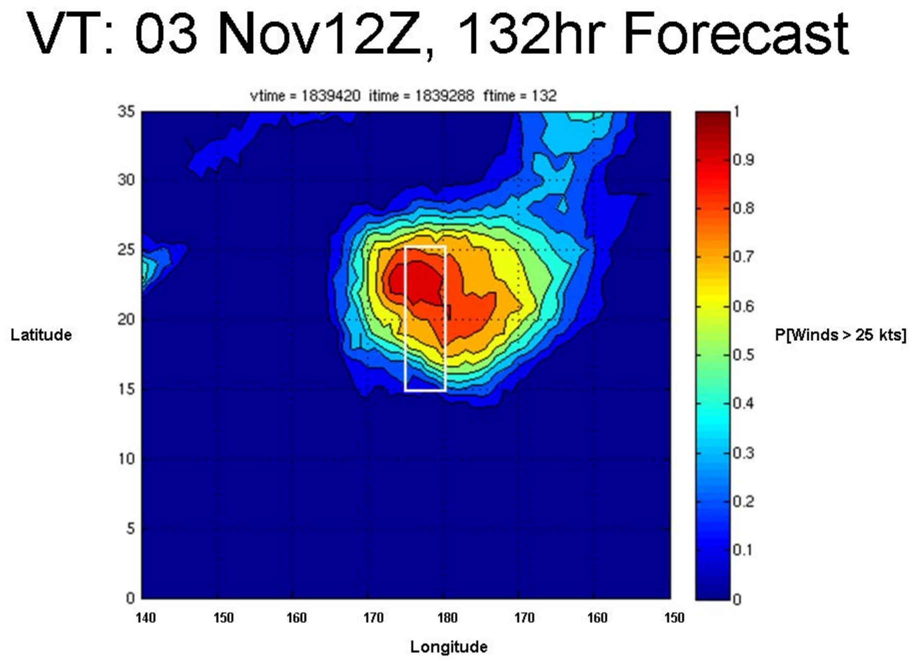


Figure 102. Probability map for valid time 3 November, 12Z; 132 hr forecast.

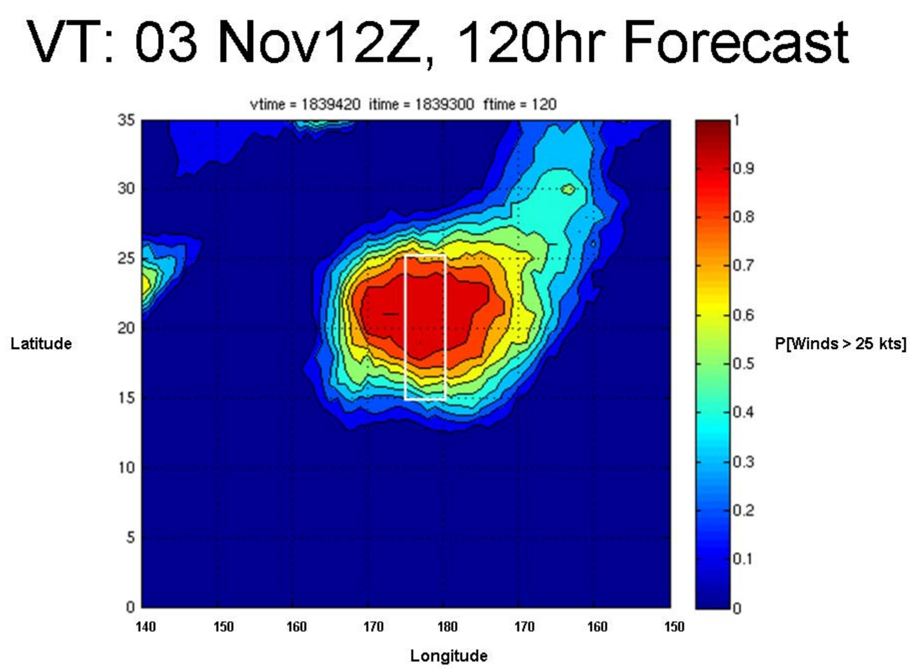


Figure 103. Probability map for valid time 3 November, 12Z; 120hr forecast.

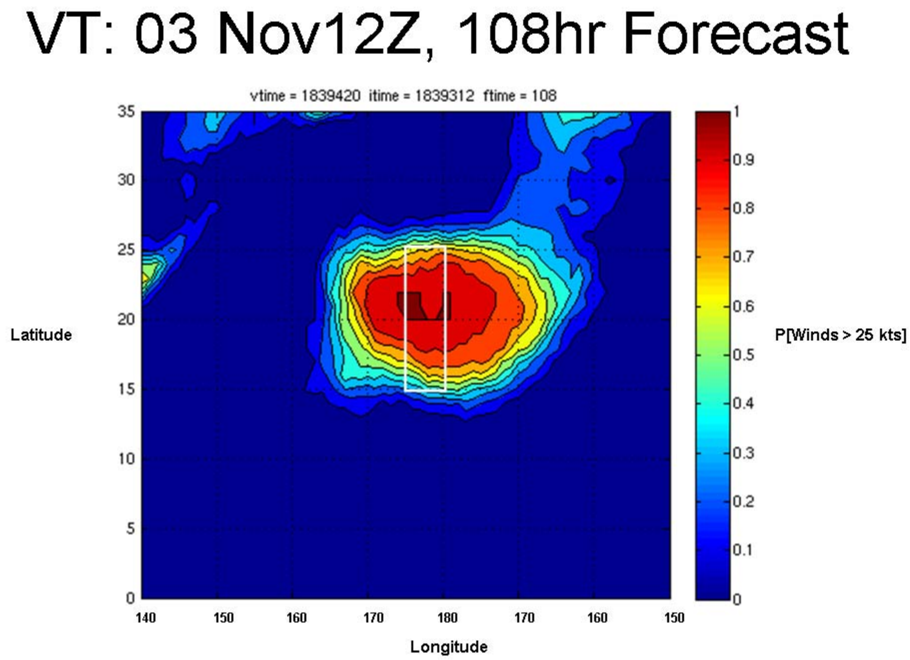


Figure 104. Probability map for valid time 3 November, 12Z; 108 hr forecast.

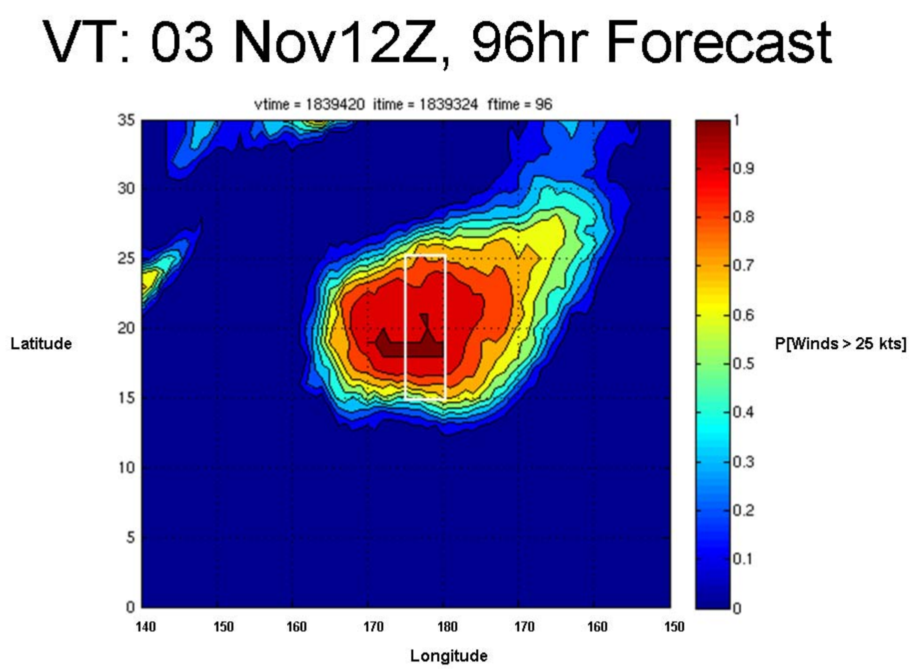


Figure 105. Probability map for valid time 3 November, 12Z; 96 hr forecast.

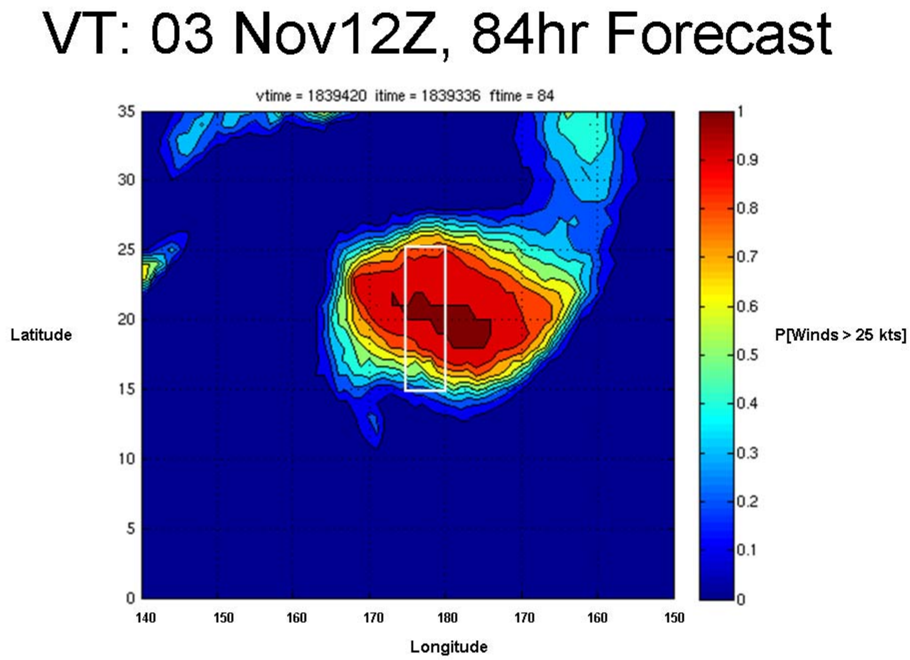


Figure 106. Probability map for valid time 3 November, 12Z; 84 hr forecast.

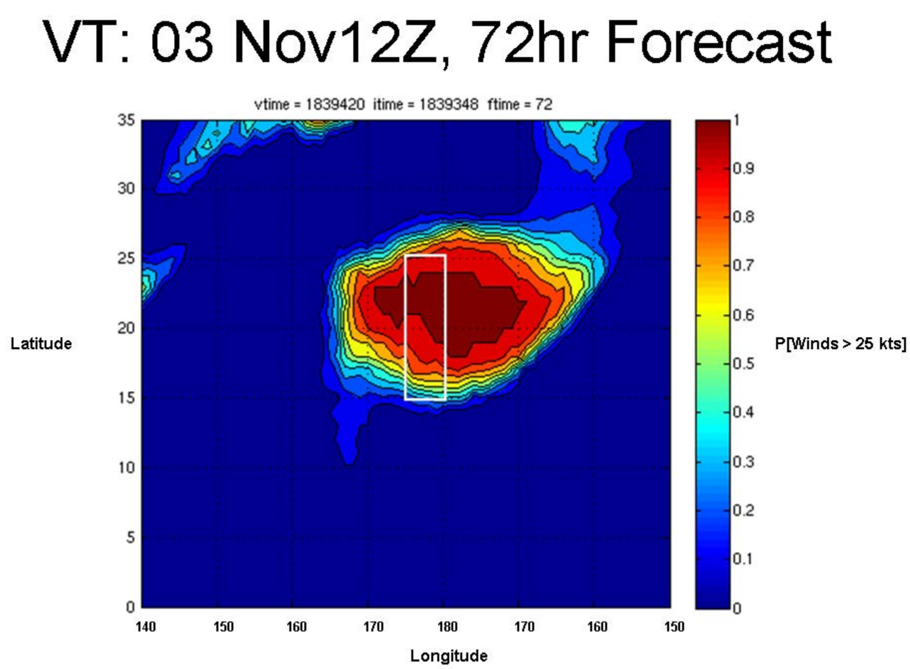


Figure 107. Probability map for valid time 3 November, 12Z; 72 hr forecast.

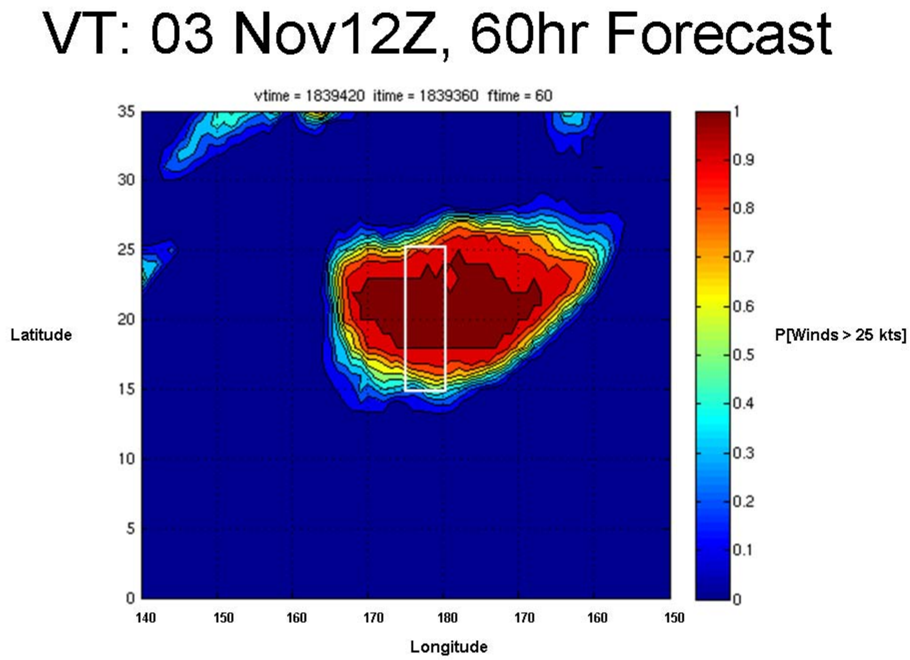


Figure 108. Probability map for valid time 3 November, 12Z; 60 hr forecast.

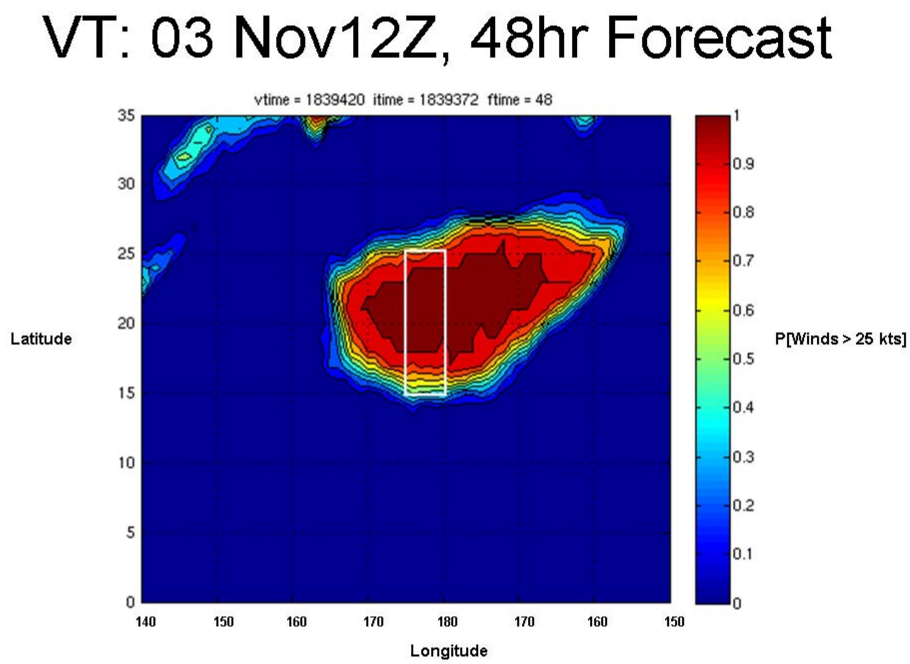


Figure 109. Probability map for valid time 3 November, 12Z; 48 hr forecast.

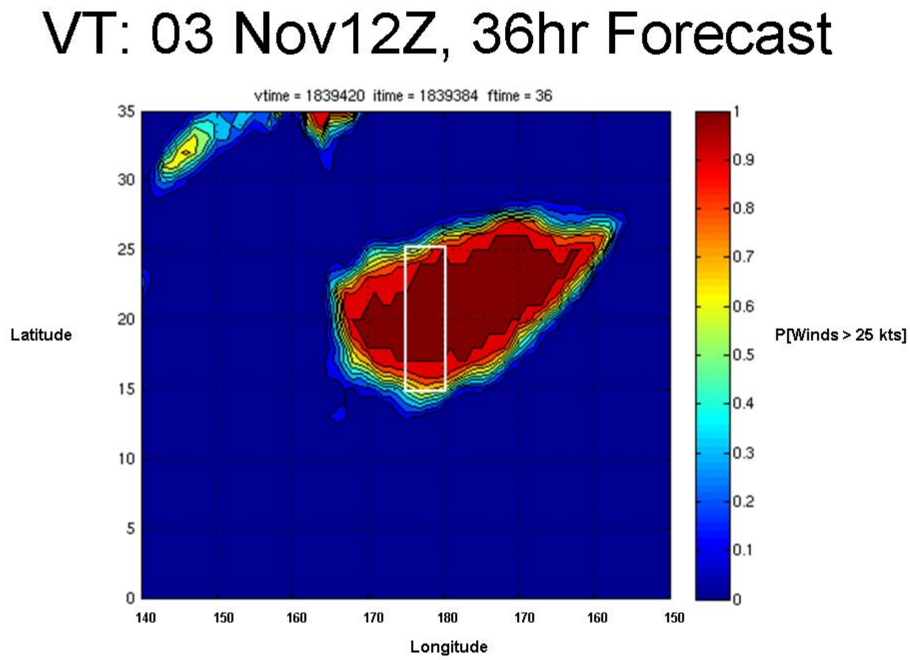


Figure 110. Probability map for valid time 3 November, 12Z; 36 hr forecast.

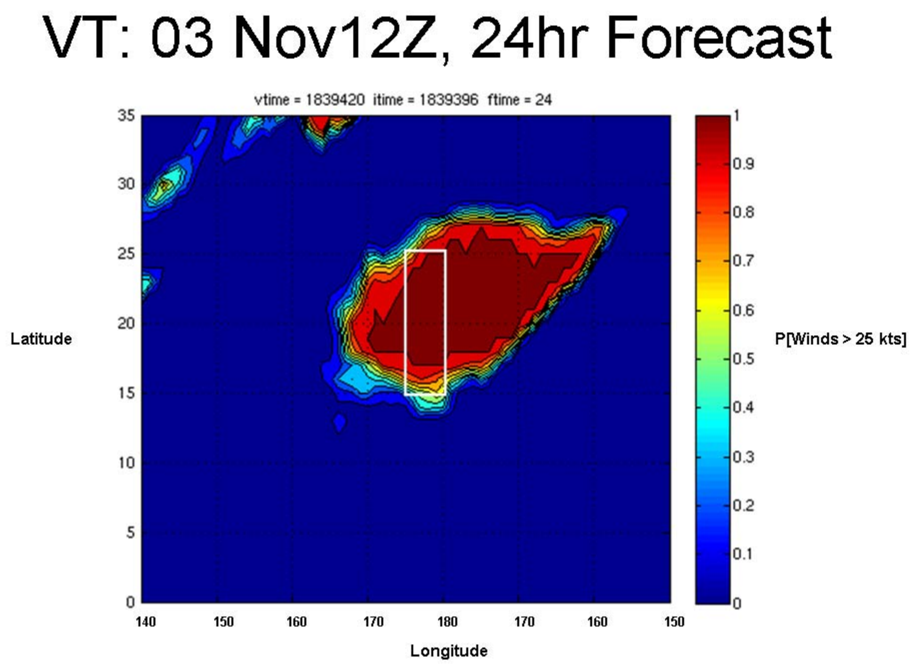


Figure 111. Probability map for valid time 3 November, 12Z; 24 hr forecast.

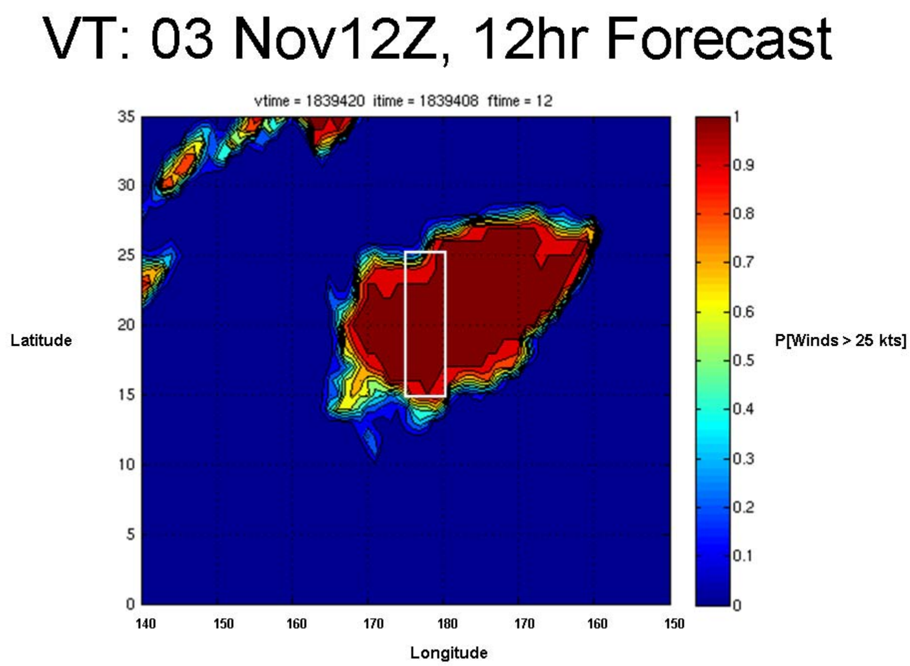


Figure 112. Probability map for valid time 3 November, 12Z; 12 hr forecast.

# APPENDIX D: PROBABILITY VS. EXPECTED DISTANCE

## A. JANUARY 2009

### 1. OZ Entry: 25 January, 12Z; Consequence: 500 km

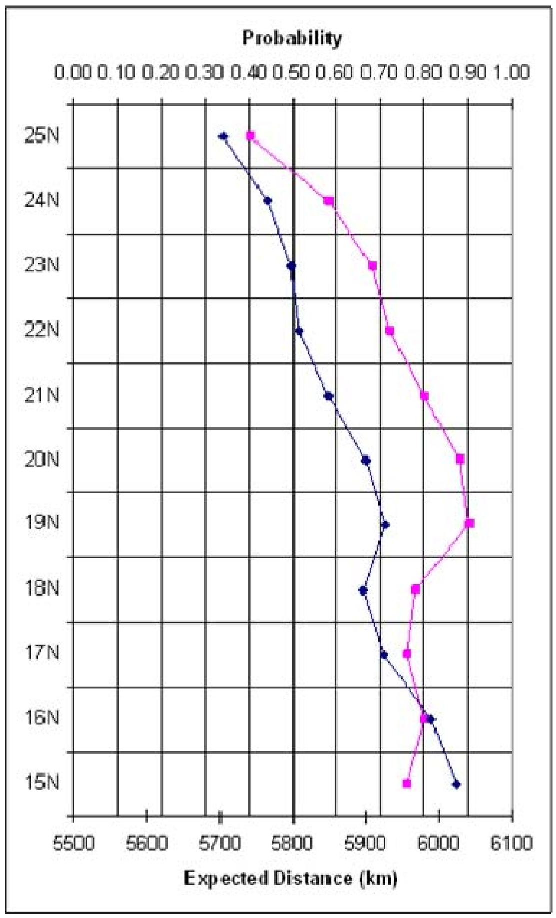


Figure 113. Probability and expected distance for 25 January, 12Z OZ entry and 500 km consequence (-5 days).

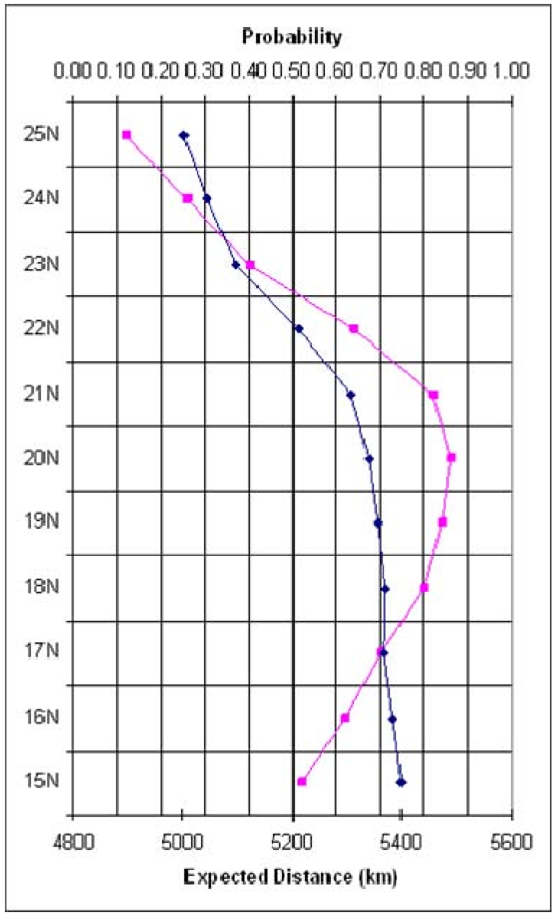


Figure 114. Probability and expected distance for 25 January, 12Z OZ entry and 500 km consequence (-4 days).

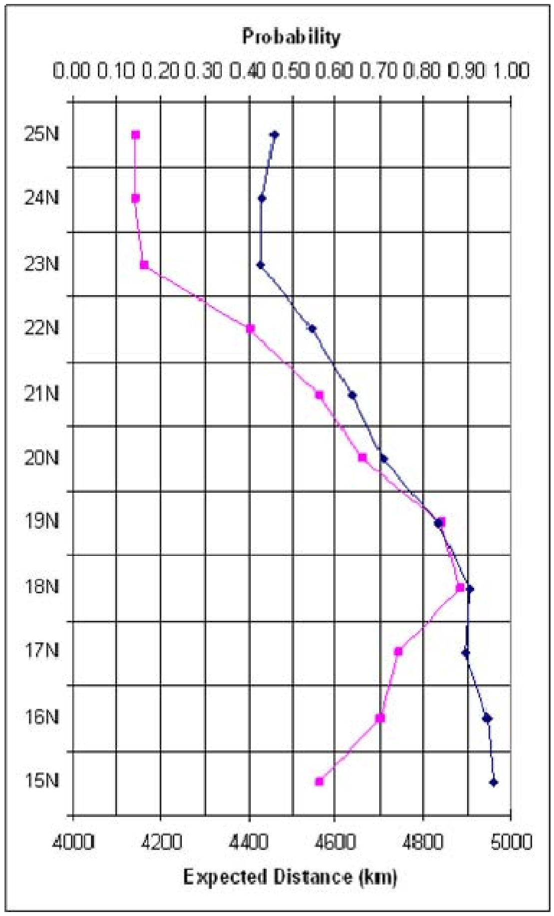


Figure 115. Probability and expected distance for 25 January, 12Z OZ entry and 500 km consequence (-3 days).

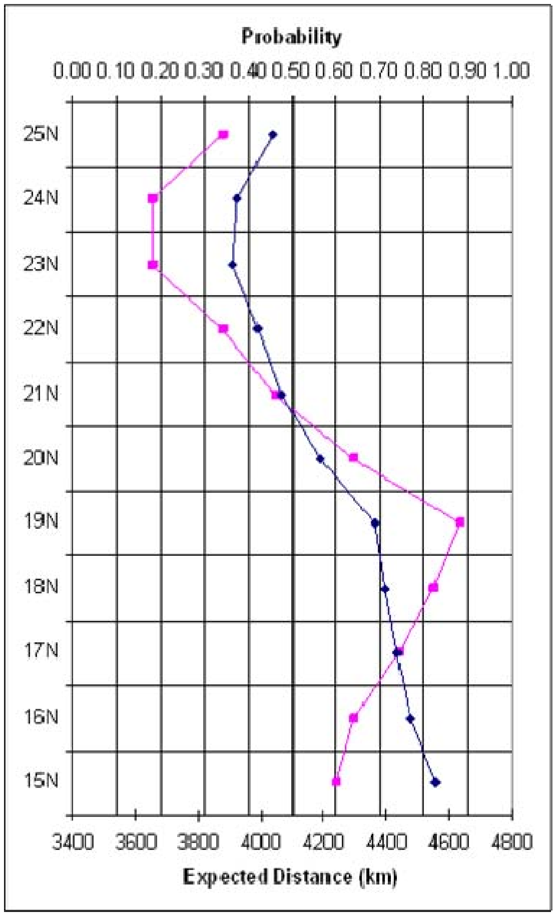


Figure 116. Probability and expected distance for 25 January, 12Z OZ entry and 500 km consequence (-2 days).

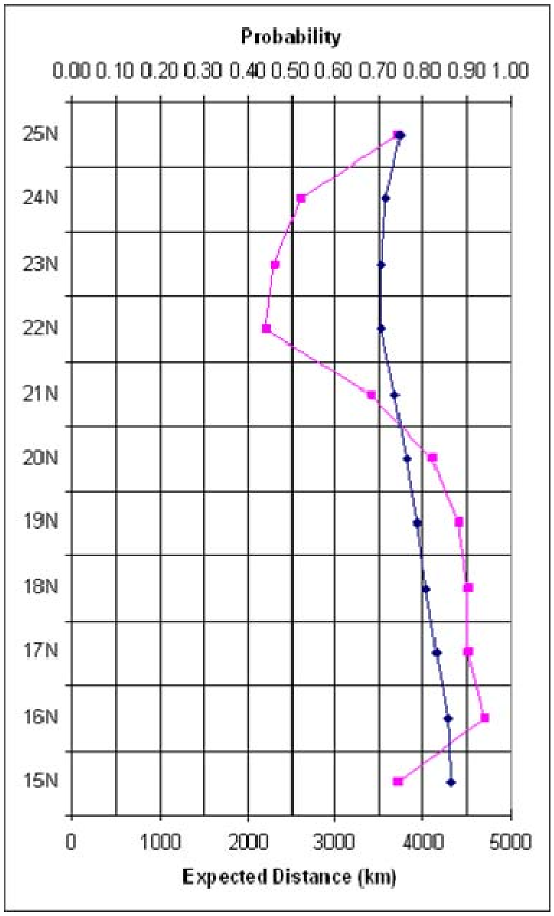


Figure 117. Probability and expected distance for 25 January, 12Z OZ entry and 500 km consequence (-1 days).

## 2. OZ Entry: 25 January, 12Z; Consequence: 1000 km

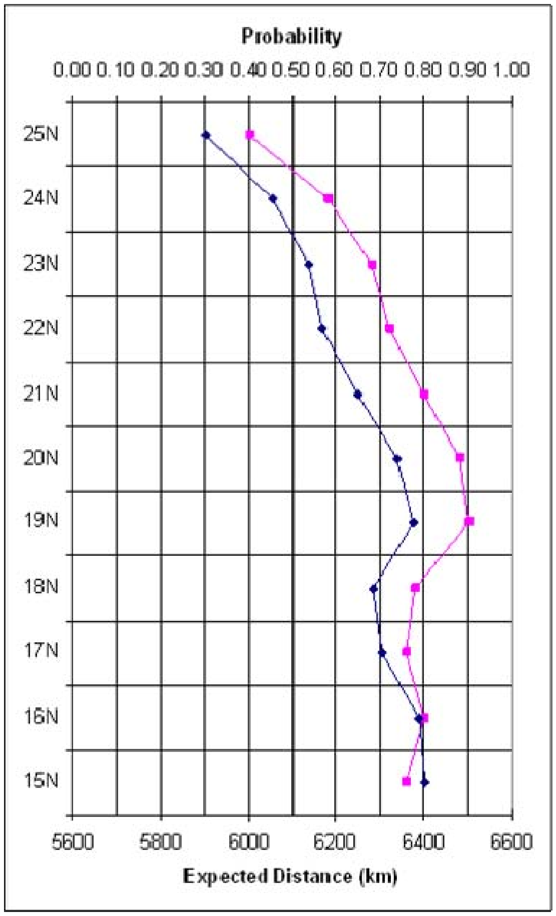


Figure 118. Probability and expected distance for 25 January, 12Z OZ entry and 1000 km consequence (-5 days).

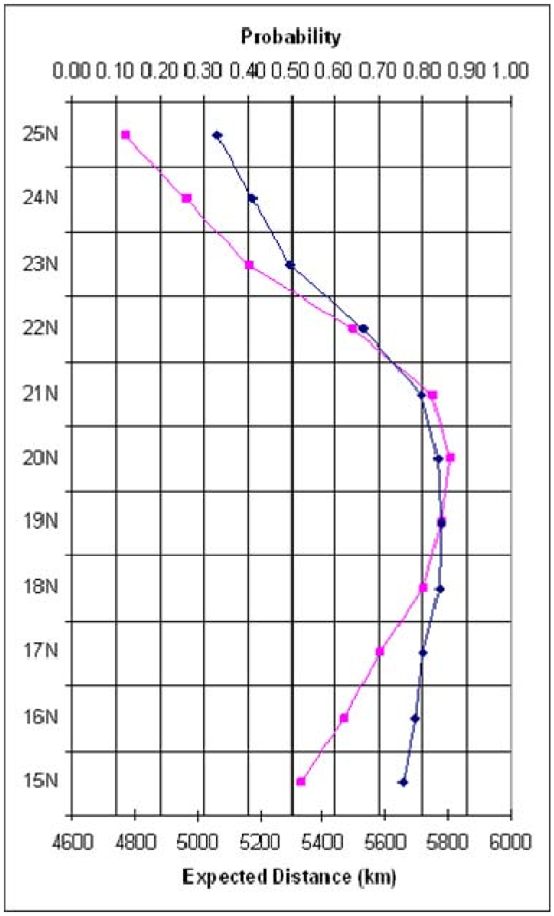


Figure 119. Probability and expected distance for 25 January, 12Z OZ entry and 1000 km consequence (-4 days).

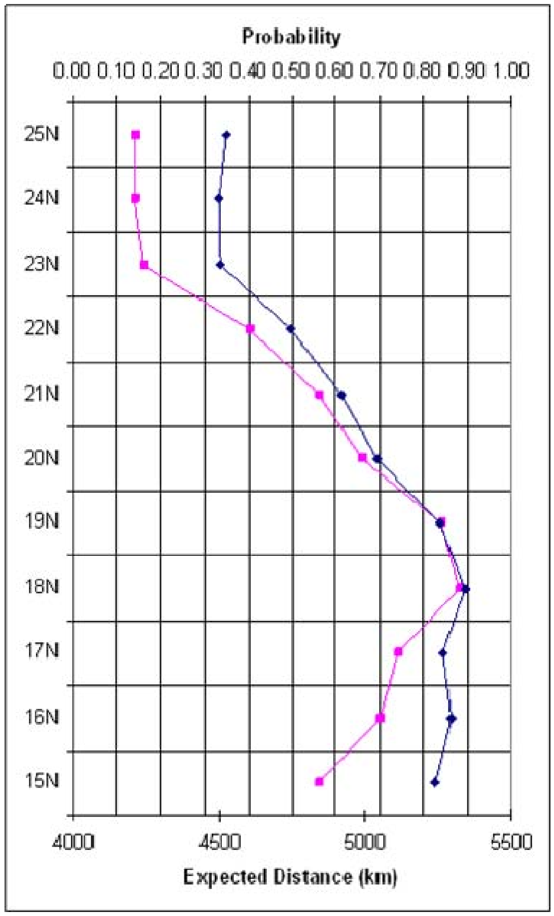


Figure 120. Probability and expected distance for 25 January, 12Z OZ entry and 1000 km consequence (-3 days).

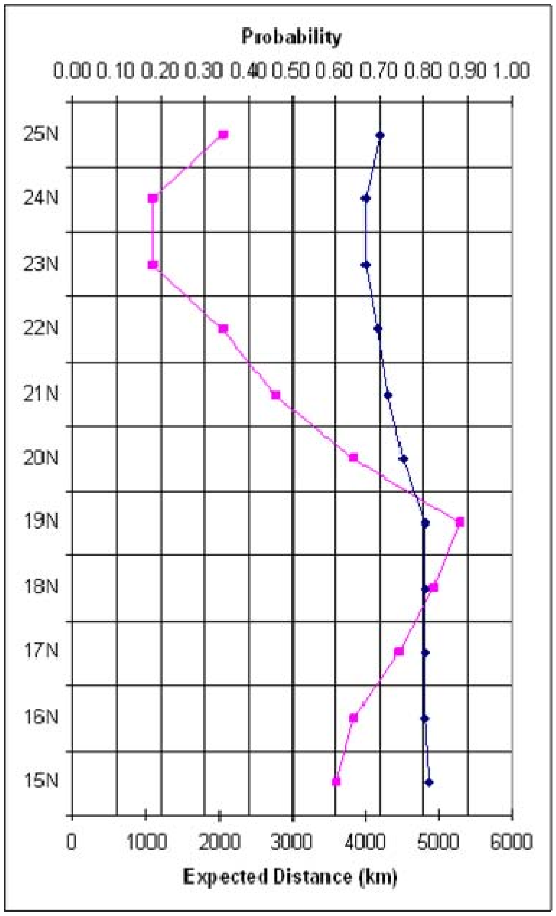


Figure 121. Probability and expected distance for 25 January, 12Z OZ entry and 1000 km consequence (-2 days).

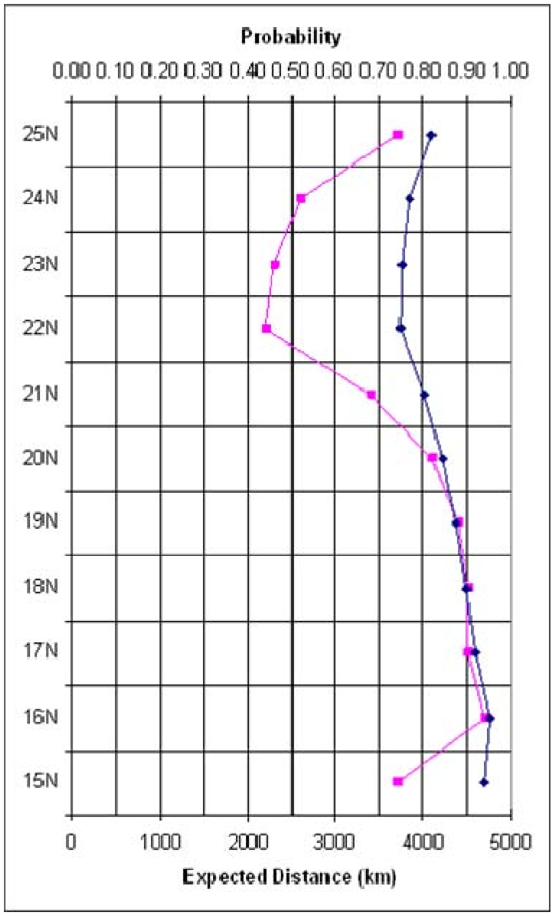


Figure 122. Probability and expected distance for 25 January, 12Z OZ entry and 1000 km consequence (-1 days).

## B. NOVEMBER 2009

### 1. OZ Entry: 3 November, 12Z; Consequence: 500 km

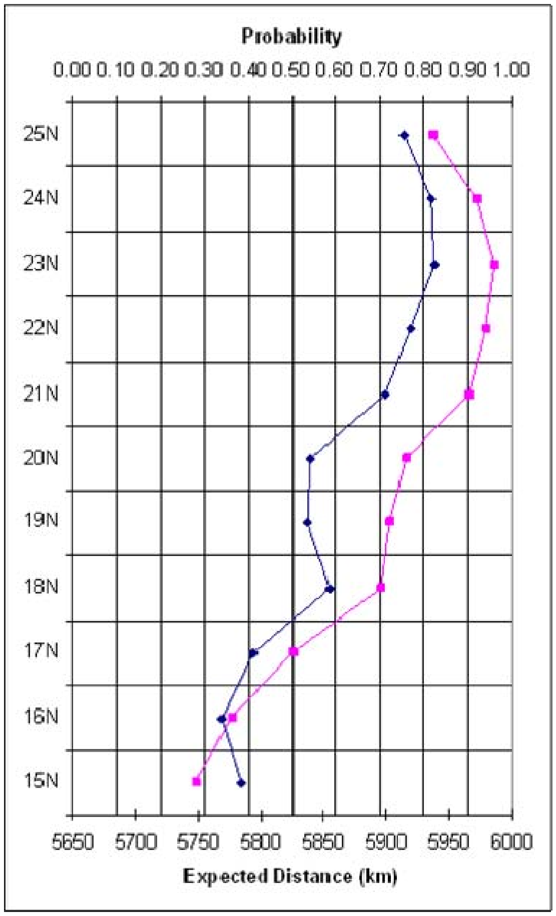


Figure 123. Probability and expected distance for 3 November, 12Z OZ entry and 500 km consequence (-5 days).

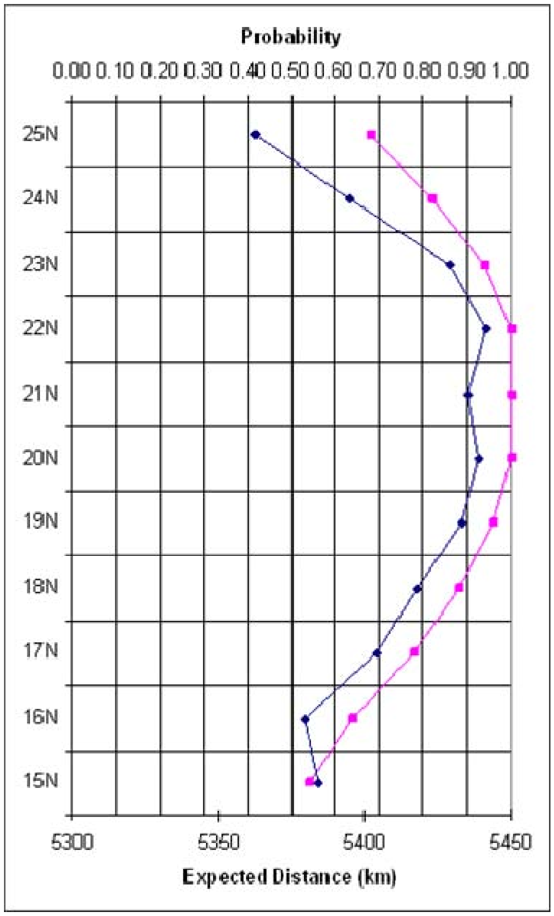


Figure 124. Probability and expected distance for 3 November, 12Z OZ entry and 500 km consequence (-4 days).

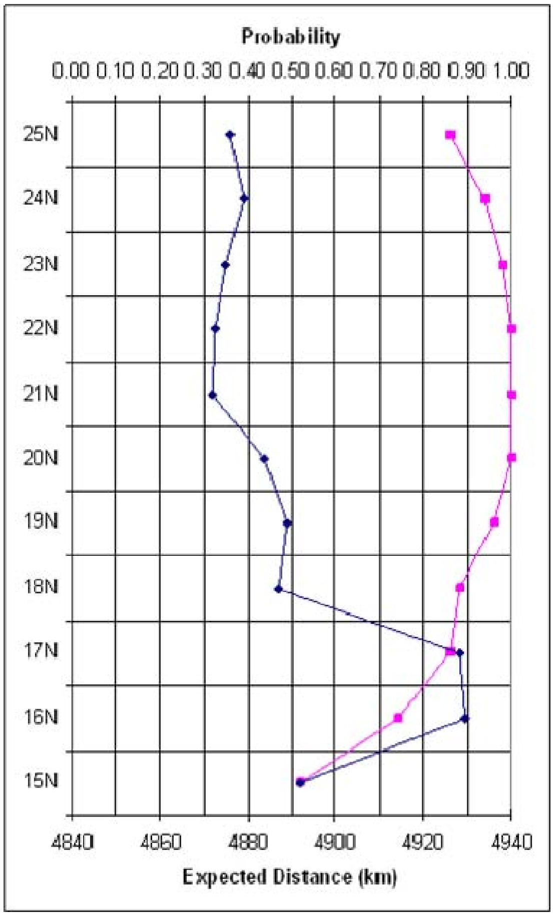


Figure 125. Probability and expected distance for 3 November, 12Z OZ entry and 500 km consequence (-3 days).

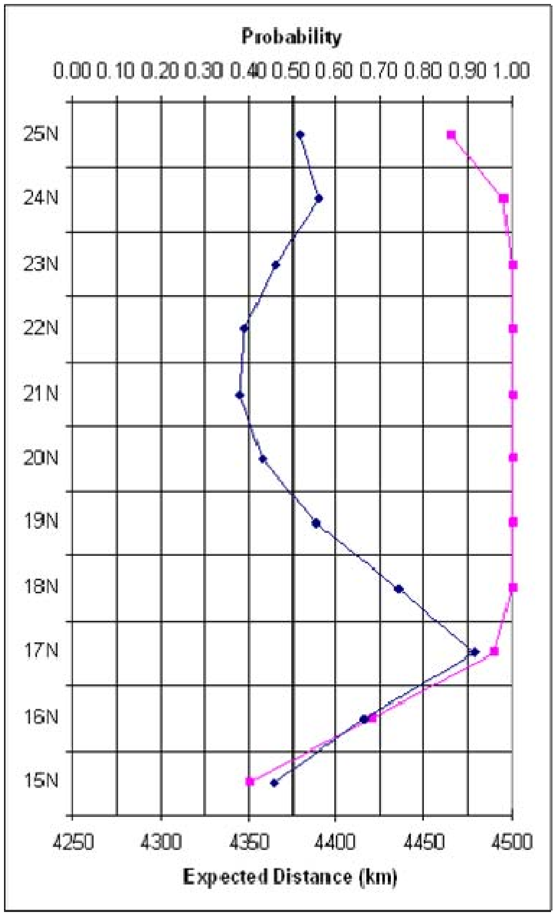


Figure 126. Probability and expected distance for 3 November, 12Z OZ entry and 500 km consequence (-2 days).

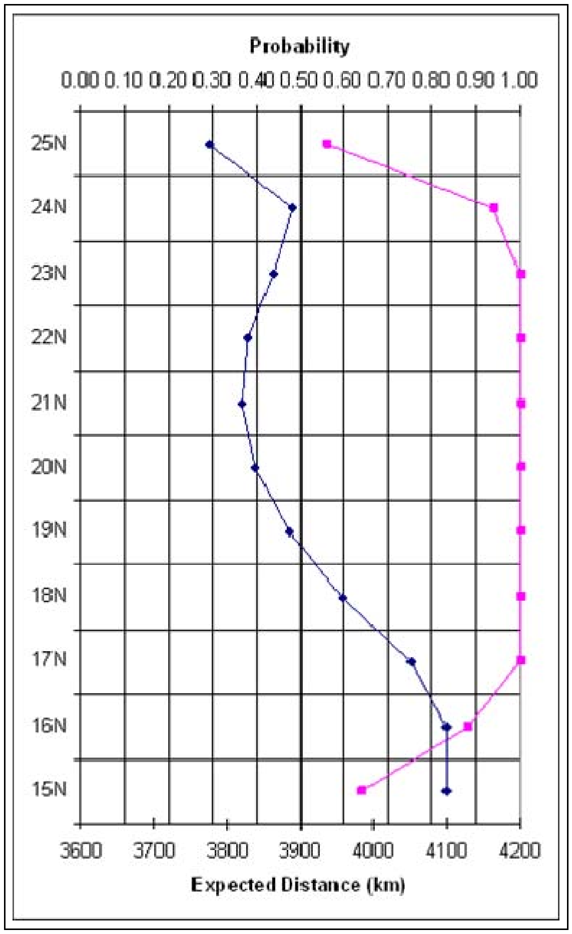


Figure 127. Probability and expected distance for 3 November, 12Z OZ entry and 500 km consequence (-1 days).

## 2. OZ Entry: 3 November, 12Z; Consequence: 1000 km

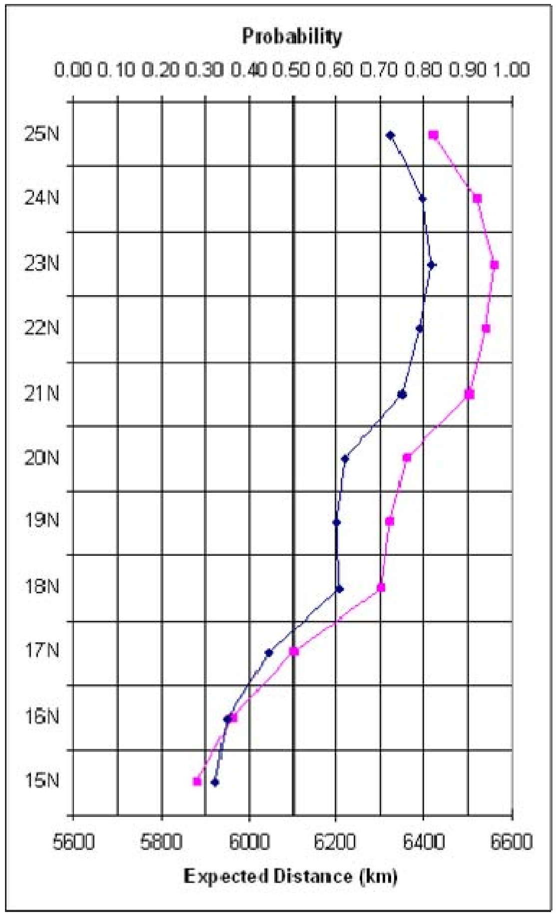


Figure 128. Probability and expected distance for 3 November, 12Z OZ entry and 1000 km consequence (-5 days).

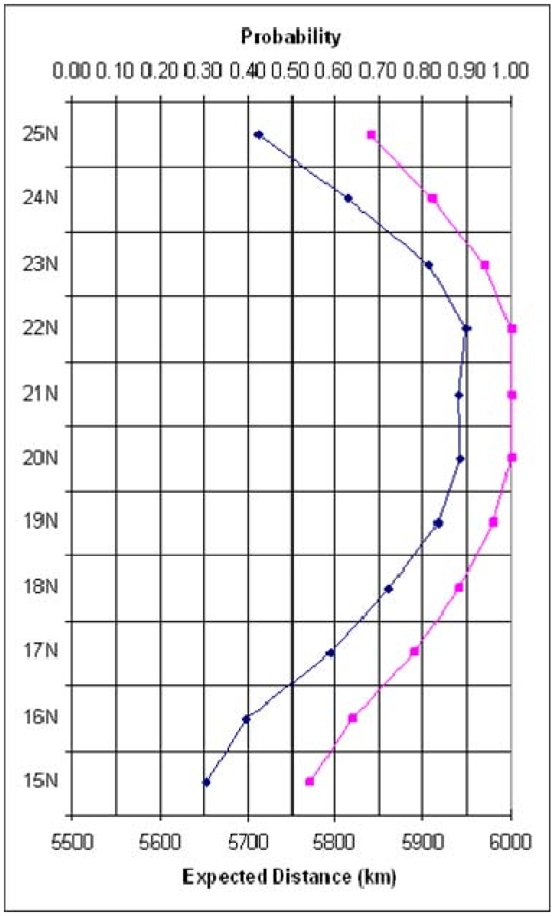


Figure 129. Probability and expected distance for 3 November, 12Z OZ entry and 1000 km consequence (-4 days).

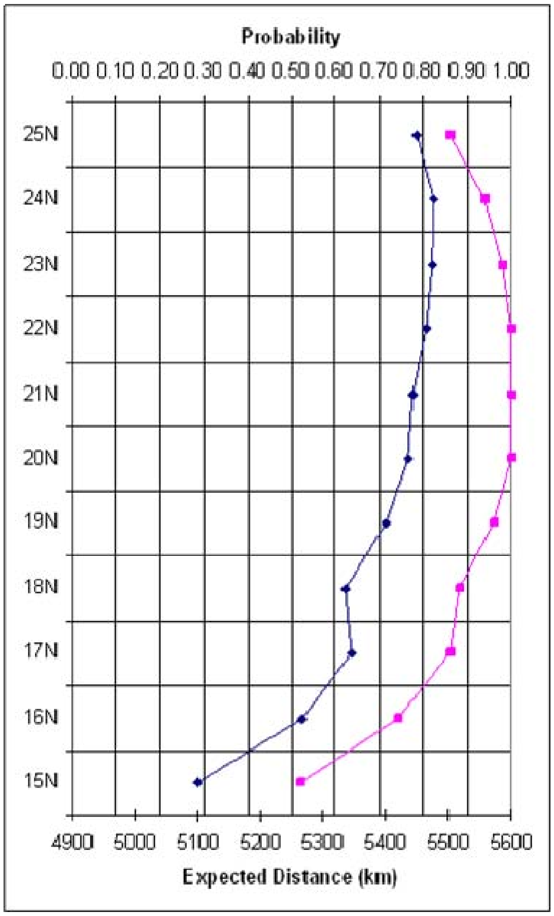


Figure 130. Probability and expected distance for 3 November, 12Z OZ entry and 1000 km consequence (-3 days).

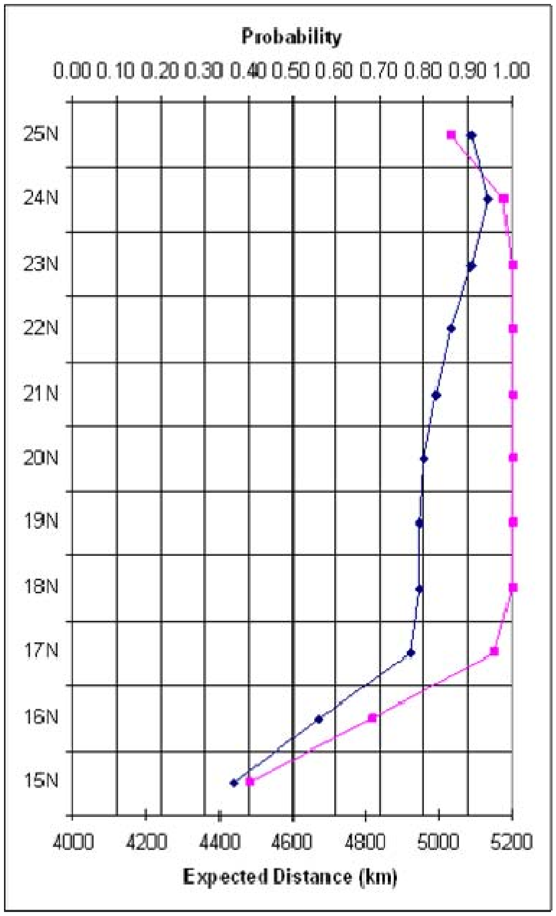


Figure 131. Probability and expected distance for 3 November, 12Z OZ entry and 1000 km consequence (-2 days).

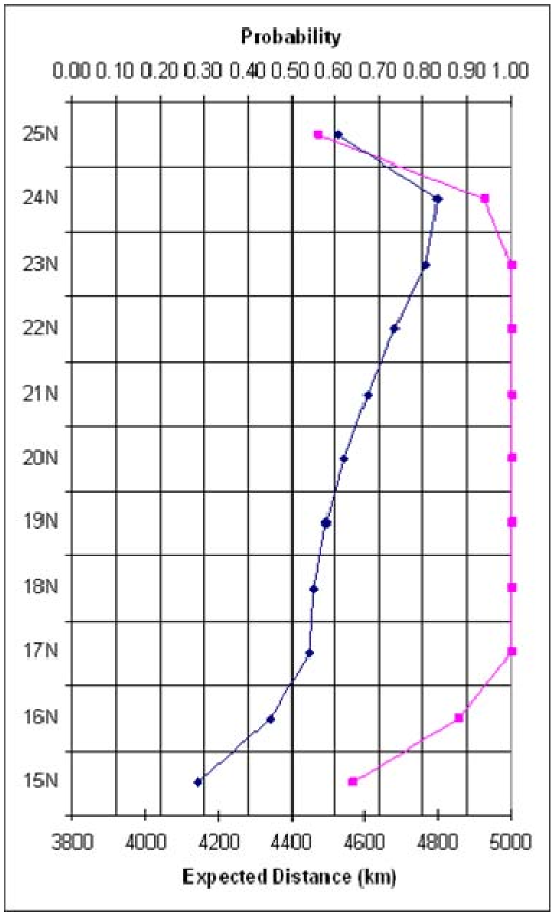


Figure 132. Probability and expected distance for 3 November, 12Z OZ entry and 1000 km consequence (-1 days).

# LIST OF REFERENCES


Advanced Climate Analysis and Forecasting. (2010). [Data set and graphics]. Retrieved from http://173.8.47.129/smartclimo/branches/csi_7_22_10/html/

Clemen, R. T. (1996). *Making hard decisions: An introduction to decision analysis*. Belmont, CA: Duxbury Press.

Commander Naval Meteorology and Oceangraphy Command. (2010). *Battlespace on demand* [Graphics]. Retrieved from https://www.portal.navy.mil/cnmoc/Pages/BattlespaceOnDemand.aspx

*Completing the forecast: Characterizing and communicating uncertainty for better decisions using weather and climate forecasts.* (2006). Retrieved from National Academies Press Web site: http://www.nap.edu/catalog.php?record_id=11699

Cooke, W. E. (1906). Weighting forecasts. *Monthly Weather Review, 34,* 274-275.

Earth Systems Research Laboratory. (2010). *Daily mean composites* [Data set and graphics]. Retrieved from http://www.esrl.noaa.gov/psd/data/composites/day/

Earth Systems Research Laboratory. (2010). *6-hourly NCEP/NCAR reanalysis data composites* [Data set and graphics]. Retrieved from http://www.esrl.noaa.gov/psd/data/composites/hour/

European Centre for Medium-Range Weather Forecasts. (2010). *The ensemble prediction system (EPS)* [Forecast product description]. Retrieved from http://www.ecmwf.int/products/forecasts/guide/The_Ensemble_Prediction_System_EPS_1.html

Moveable Type, Ltd. (2010). *Calculate distance, bearing and more between latitude/longitude points* [Distance calculator]. Retrieved from http://www.movable-type.co.uk/scripts/latlong.html

Murphy, A. H. (1993). What is a good forecast? An essay on the nature of goodness in weather forecasting. *Weather and Forecasting, 8,* 281–293.

Remote Sensing Systems. (2010). *SSM/I dynamic: daily* [Data set and graphics]. Retrieved from http://www.remss.com/idx/ion-p.exe?page=ssmi_daily.ion

Zhu, Y., Toth, Z., Wobus, R., Richardson, D., & Myline, K. (2002). The economic value of ensemble-based weather forecasts. *Bulletin of the American Meteorological Society, 83*(1), 73–83.

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